

**DESIGN OF AN UNMANNED  
LUNAR CARGO LANDER THAT  
RECONFIGURES INTO A SHELTER  
FOR A HABITATION MODULE OR  
DISASSEMBLES INTO PARTS  
USEFUL TO A PERMANENT  
MANNED LUNAR BASE**

Submitted to:  
James A. Aliberti

**NATIONAL AERONAUTICS AND SPACE  
ADMINISTRATION**

Advanced Projects, Technology and Commercialization Office

Prepared by:

Lisa Davanay  
Brian Garner, Team Leader  
Jason Rigol

Mechanical Engineering Department  
**THE UNIVERSITY OF TEXAS AT AUSTIN**  
Austin, Texas

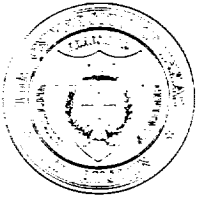
Fall 1989

(NASA-CR-186687) DESIGN OF AN UNMANNED  
LUNAR CARGO LANDER THAT RECONFIGURES INTO A  
SHELTER FOR A HABITATION MODULE OR  
DISASSEMBLES INTO PARTS USEFUL TO A  
PERMANENT MANNED LUNAR BASE (Texas Univ.)

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MECHANICAL ENGINEERING DESIGN PROJECTS PROGRAM

THE UNIVERSITY OF TEXAS AT AUSTIN

ETC 4.102 • Austin, Texas 78712-1063 • (512) 471-3900

November 15, 1989

James A. Aliberti  
Manager of Research Programs  
Mail Stop PT-PMO  
Kennedy Space Center, FL 32899

Dear Mr. Aliberti:

Please find enclosed our report entitled "Design of an Unmanned Lunar Cargo Lander that Reconfigures into a Shelter for a Habitation Module or Disassembles into Parts Useful to a Permanent Manned Lunar Base." The report contains background information, project requirements and criteria, basic assumptions, alternate designs, the final design and accompanying scenario, conclusions, and recommendations.

The design team is pleased to invite you to attend the Mechanical Engineering Design Projects Program oral presentation of our project. The presentation is scheduled for December 5, 1989 at 8:00 a.m. in room 4.110 of the Engineering Teaching Center on The University of Texas at Austin campus. There will also be a subsequent catered luncheon.

Sincerely,

*Lisa Davanay*  
Lisa Davanay

*Brian Garner*  
Brian Garner, Team Leader

*Jason Rigol*  
Jason Rigol

## ACKNOWLEDGEMENTS

The design team would like to thank USRA and Mr. James Aliberti of NASA for sponsoring this project. Special thanks also goes to the design team's lab instructor, Mr. Richard Connell, who provided invaluable guidance and inspiration to all the NASA/USRA-sponsored teams. In addition, Dr. Bob Freeman was a great help as the design team's faculty advisor. Dr. David Bourell and Dr. Stelios Kyriakides also deserve special thanks for sharing their knowledge of materials.

Particularly valuable to the progress of the project were professors Dr. Wallace Fowler and Dr. George Botbyl and graduate students Mr. George Davis and Mr. Steve Hirshorn of the UT-Austin Aerospace Department. Their expertise in space and lunar base activities was essential for a complete understanding of the project background and lunar base scenarios. Finally, the design team would like to thank Dr. Steven Nichols, Mr. Wendell Deen, and Mr. Bert Hergistad for their guidance in the design process throughout the semester.

## ABSTRACT

### DESIGN OF AN UNMANNED LUNAR CARGO LANDER THAT RECONFIGURES INTO A SHELTER FOR A HABITATION MODULE OR DISASSEMBLES INTO PARTS USEFUL TO A PERMANENT MANNED LUNAR BASE

NASA plans to establish a permanent manned lunar base by the first decade of the twenty-first century. It is extremely expensive to transport material from Earth to the moon. Therefore, expense would be reduced if the vehicle that lands cargo on the moon could itself meet some of the material needs of establishing the lunar base. The report describes the design of a multi-functional lander that is entirely useful to the base after landing.

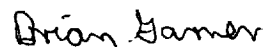
The report contains alternate designs of the overall lander configuration and possible uses of the lander and its components after landing. The design solution is a lander employing the Saddlebagged Fuel Tank Configuration. After landing, its structure will be converted into a habitation module shelter that supports a protective layer of regolith. The fuel tanks will be cleaned and used as storage tanks for the lunar base. The engines and instrumentation will be saved as stock parts.

The report concludes with recommendations for further research and technology development to enhance future lander designs.

**KEY WORDS:** LUNAR BASE, LUNAR CARGO LANDER, MULTI-FUNCTIONAL LANDER, RADIATION PROTECTION, HABITATION MODULE SHELTER, POST-LANDING FUNCTION



Lisa Davanay



Brian Garner, Team Leader



Jason Rigol

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## INTRODUCTION

The Universities Space Research Association (USRA) is a Houston-based consortium of universities dedicated to the exploration and development of space. Organized in 1969 by the National Academy of Sciences, USRA coordinates public and private interests in advancing space technology. With USRA as a conduit, the United States National Aeronautics and Space Administration (NASA) is currently sponsoring graduate and senior engineering design teams at The University of Texas at Austin (UT) for research in the design and development of a permanent manned lunar base.

This report describes the design of an unmanned lunar cargo lander that has post-landing functions useful to a permanent manned lunar base. The first chapter contains background information, project requirements and criteria, basic assumptions, and the design methodology. The second chapter presents alternate designs of overall lander configuration and post-landing functions. The next chapter describes the chosen design solution and a lunar scenario depicting its implementation. The final chapter presents conclusions and recommendations.

## BACKGROUND

Currently NASA intends to establish a permanent manned lunar base by the early twenty-first century. Extraction of lunar oxygen (LUNOX) from lunar soil for fuel and life support, and competition from other nations in the development of space technology are the primary reasons for

establishing a lunar base. Construction of a manned lunar base will require the transportation of large quantities of material and equipment from Earth to the moon. The cost of transporting one pound of material to the moon is approximately one million dollars. Therefore, to reduce time and cost, it is desirable to maximize the usefulness of all equipment sent to the moon.

A critical component in the transport of equipment from Earth to the moon is the lunar lander, which is assembled and loaded in low earth orbit, propelled to low lunar orbit, and used to transport cargo from low lunar orbit to the lunar surface (see Figure 1). Although the lunar landers used in the Apollo missions successfully completed the missions they were designed for, they would not be practical in developing a lunar base because they were not designed for reuse after the crew module departed from the lunar surface. Therefore, the team has designed a lander that has post-landing capabilities useful to the establishment and/or operation of a lunar base.

### PROJECT REQUIREMENTS

The design team was requested to meet the following project requirements:

1. Design a lunar lander that can safely transport cargo from low earth orbit to the lunar surface and then transform in some way to perform another function or functions useful to the lunar base.
2. Construct a demonstration model which shows landing vehicle configuration and key operating features.

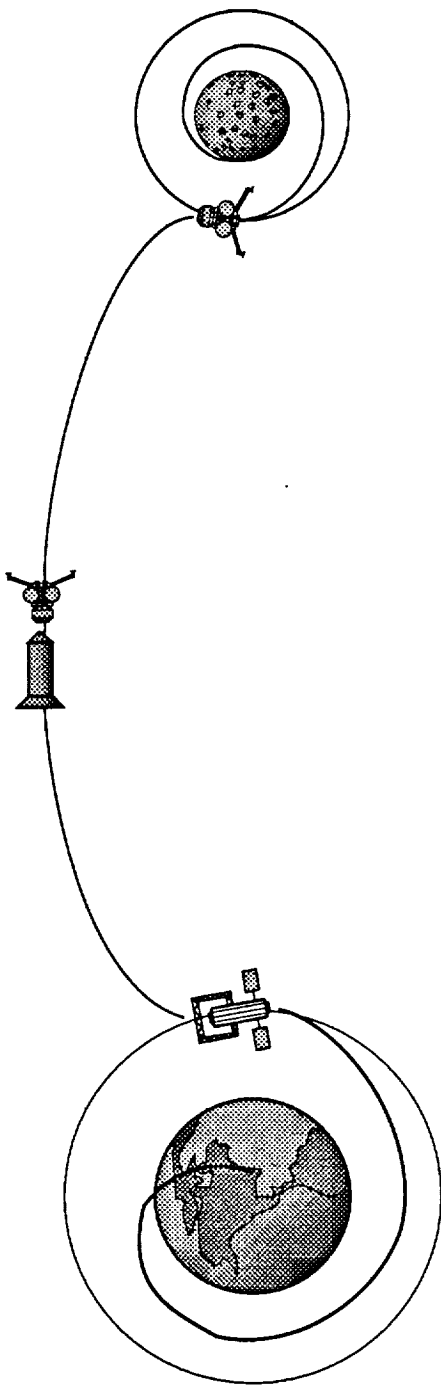


Figure 1: TRANSPORT OF CARGO FROM EARTH  
TO THE MOON

## PROJECT CRITERIA

The following project criteria were established:

1. Follow the baseline lander design for such features as shape, size, and modular components (see Figure 2).
2. Minimize lander mass to maximize allowable payload and reduce fuel requirements.
3. Simplify all lander transformations so that they may be performed automatically, robotically, or manually. Robotic and manual transformations are limited by low dexterity.
4. Design for post-landing functions that meet an immediate or early need of the lunar base.
5. Utilize the entire lander for the post-landing functions.

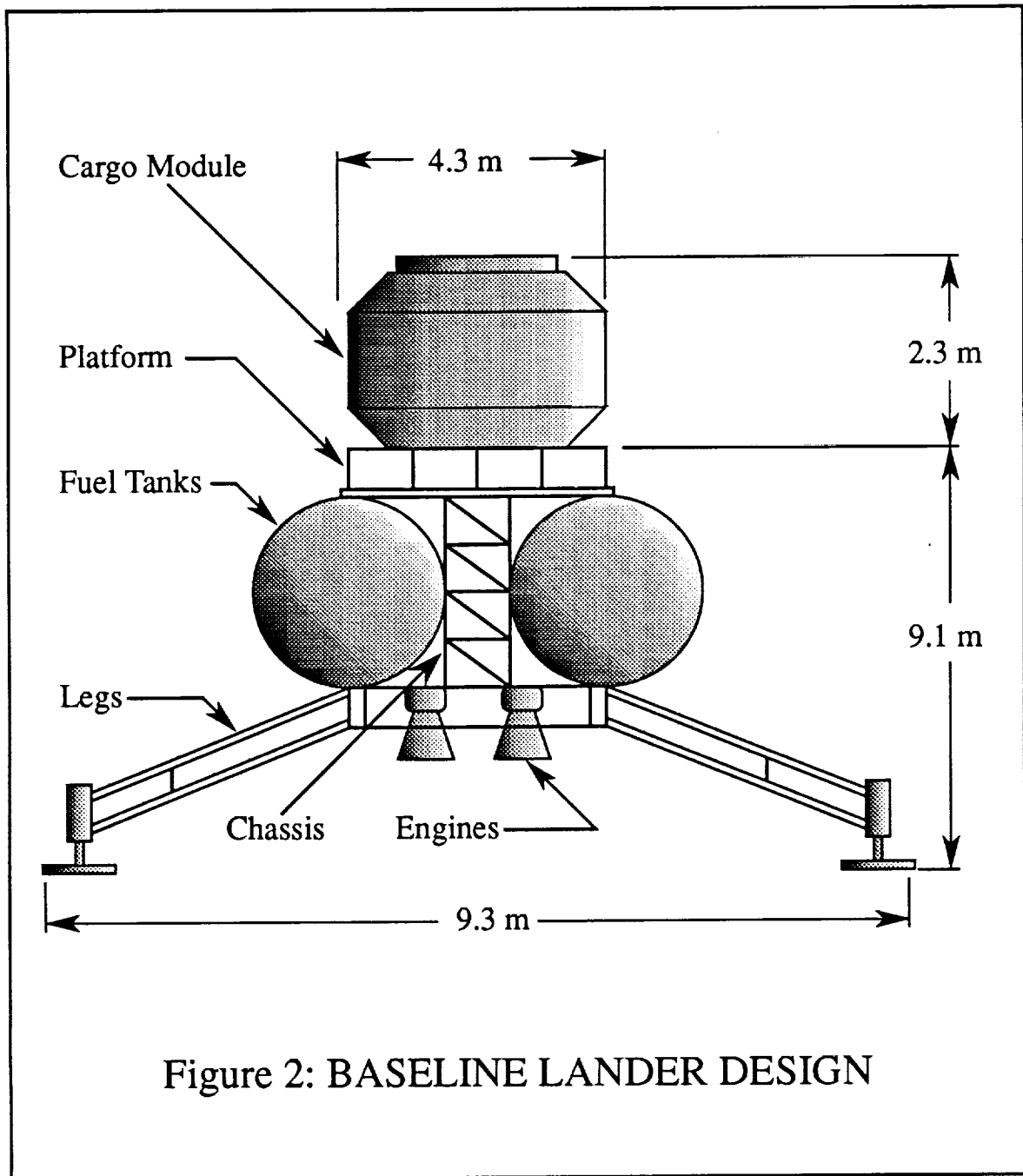
## BASIC ASSUMPTIONS

The design team made the following assumptions for the formulation of a design solution:

1. Availability of a lifting machine on the lunar surface.
2. Existence of technology for refireable rockets.
3. Capacity to clean fuel tanks on the lunar surface.
4. Availability of excavating and bag filling machinery.
5. Use of Space Station Common Modules as cargo modules (see Figure 3) [2].\*
6. Conversion of the cargo modules into habitation modules on the lunar surface.

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\* All references in this report refer to the numbered references on page 51.



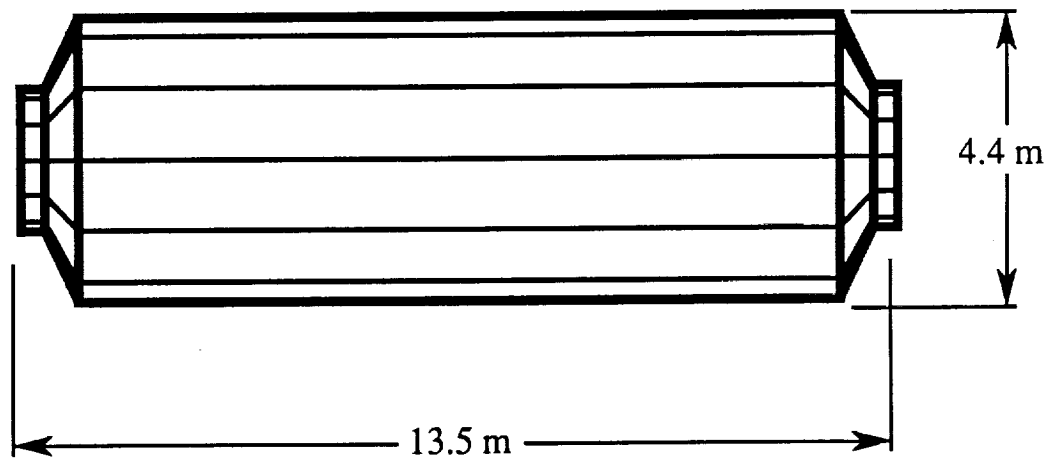


Figure 3: SPACE STATION COMMON MODULE

## DESIGN METHODOLOGY

The design team has developed a lunar lander that meets the project requirements and criteria. We have been working in conjunction with the three other NASA/USRA sponsored project teams and the Mechanical and Aerospace Engineering Departments at UT by attending regular meetings and presentations.

The design team followed a five-step plan in developing the lunar lander.

1. Extensive Research: Conducted a literature search using UT and NASA resources and consulted experts in mechanics and lunar bases from both the Mechanical and Aerospace Engineering Departments.
2. Brainstorming: Determined the needs of a lunar base and developed design ideas for a lunar lander that could transform to meet those needs.
3. Alternate Designs: Narrowed down preliminary ideas to several promising design possibilities by considering design requirements, criteria, and the work done by the other NASA/USRA-sponsored UT project teams.
4. Design Solution: Developed in detail the optimal lander design.
5. Demonstration Model: Constructed a scaled model demonstrating operating design characteristics and functions. The model is scaled in conjunction with the other NASA/USRA-sponsored UT project teams to allow a composite demonstration exhibit.



## ALTERNATE DESIGNS

The most recent lunar base mission scenarios have suggested that the first four to six unmanned cargo landers will not be re-launched from the moon. Ideally, these landers will be used immediately and entirely for construction of the preliminary manned lunar base. Furthermore, to minimize production costs and time, these first landers will be identical in design. The following components were identified as necessary for any lander configuration.

1. Lander structure, which includes the legs, chassis, and platforms. The structure supports the cargo module, fuel tanks, engines, and instrumentation.
2. Fuel tanks, typically spherical, which hold liquid oxygen and hydrogen at cryogenic temperatures.
3. Engines and instrumentation, which are essential for propulsion and guidance. Preferably these components will be attached by quick-release mounts for easy removal.

The first part of the chapter presents ideas for the overall lander configuration that integrate the essential components into a functioning lander. Advantages and disadvantages of each idea are discussed.

The second part of the chapter identifies possible uses for these components after they have served their landing function. Due to the complex nature of the engines and instrumentation, the design team focused on the possible uses of the structure and fuel tanks only. The engines and

instrumentation will be saved for future reuse. The engines were considered only for configuration purposes, while the instrumentation was assumed to be placed almost anywhere on the lander.

### OVERALL LANDER CONFIGURATIONS

The design team considered the following objectives in addition to the project requirements and criteria when generating ideas for the overall lander configuration:

1. Locating the cargo module to facilitate its removal from the lander.
2. Arranging all components symmetrically about the central vertical axis of the lander so that the lander's center of gravity is directly above the line of thrust.
3. Positioning components reasonably far away from the engine nozzles to avoid thermal damage. Meeting this objective disallows placing the cargo module underneath the lander between engines.
4. Configuring the components to give the lander a low center of gravity for stability.
5. Compacting the overall configuration to achieve low rotational moments of inertia. Meeting this objective will reduce the amount of fuel needed to rotate the lander in space.

### Baseline Configuration

The Baseline Configuration (BC) has the cargo module stacked above the fuel tanks, which are in turn directly above the four engines (see Figure 4). This design is advantageous in that the cargo module is far

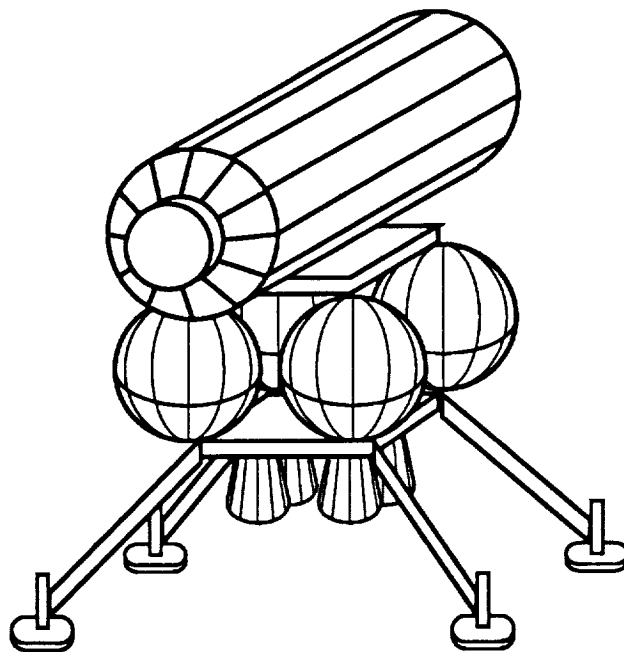
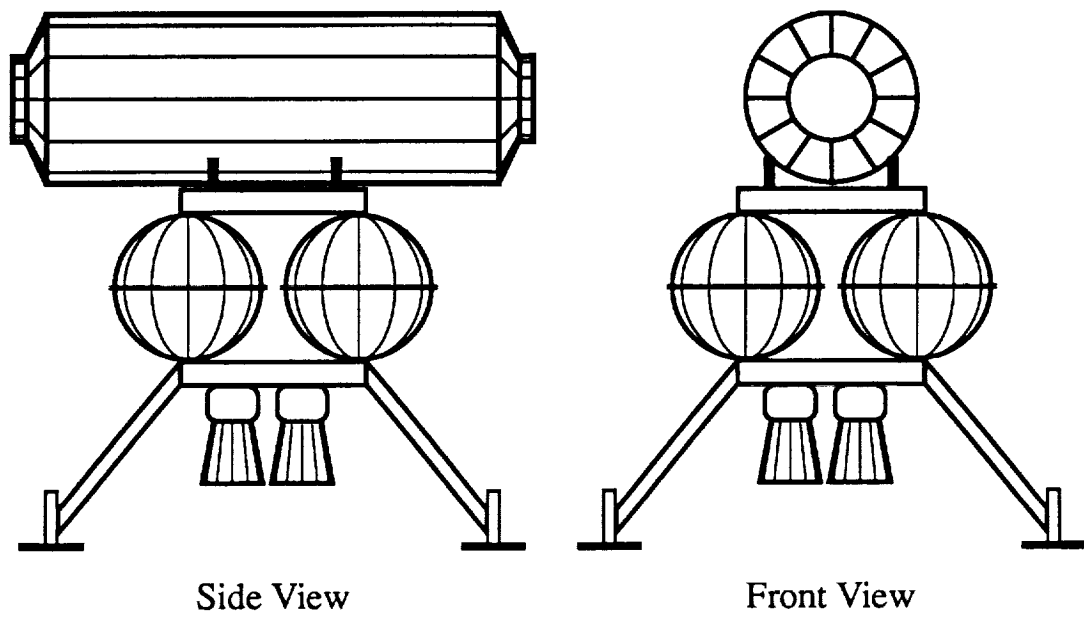


Figure 4: BASELINE CONFIGURATION

from the engine blast. However, the design is disadvantageous in that it has a fairly high center of gravity and high rotational moments of inertia about axes in the horizontal plane.

### Modified Baseline Configuration

The Modified Baseline Configuration (MBC) is like the BC except that the legs are attached to the cargo platform rather than the engine platform (see Figure 5). Because of the higher attachment points for the legs, the legs are longer than those of the BC. This design is advantageous if the structure is used as a garage or shelter which must have a high clearance. However, like the BC, the center of gravity and the rotational moments are both relatively high.

### Saddlebagged Fuel Tank Configuration

The Saddlebagged Fuel Tank Configuration (SFTC) has one platform upon which the cargo module is mounted between two pairs of fuel tanks (see Figure 6). It is advantageous in that the cargo module is positioned one fuel tank diameter lower than in the BC and MBC. This factor provides for a lower center of gravity for the vehicle and easier access to the cargo module. Furthermore, because the fuel tanks are not clustered in the center of the lander they are more exposed for physical inspection. Another advantage of the SFTC is that only one platform is required, simplifying the design. However, this platform will need to be

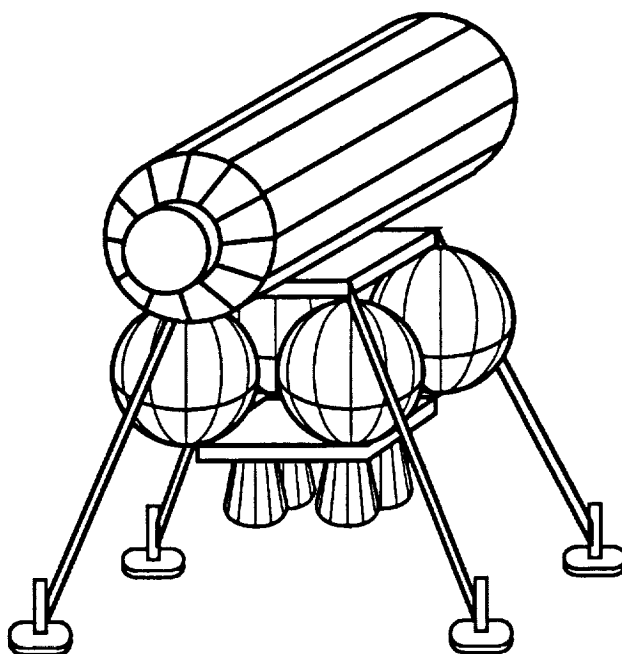
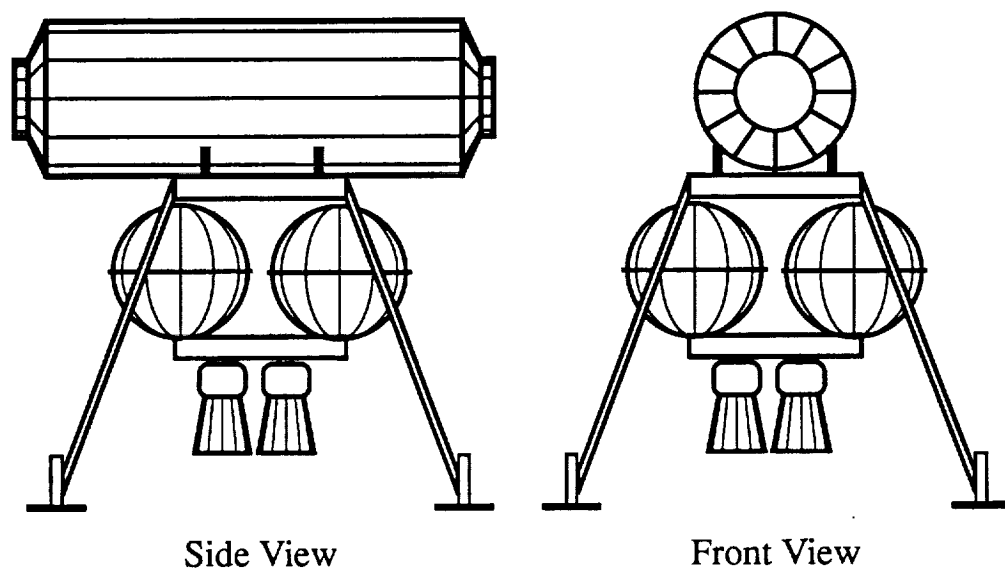
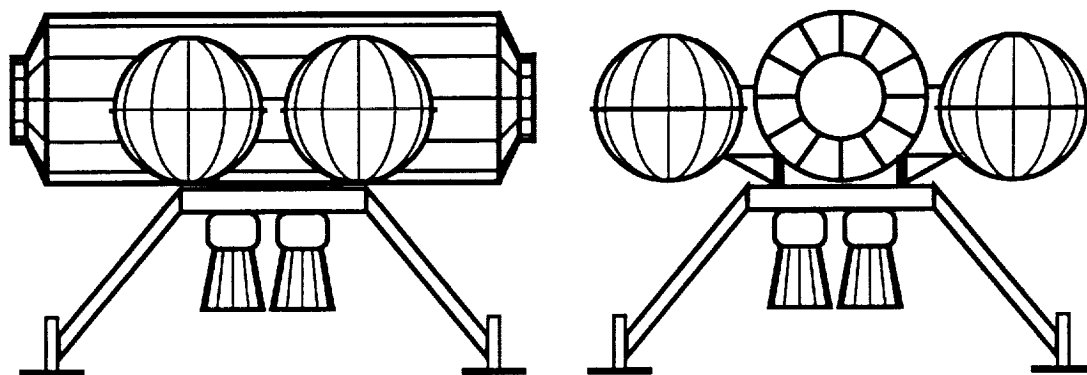


Figure 5: MODIFIED BASELINE CONFIGURATION



Side View

Front View

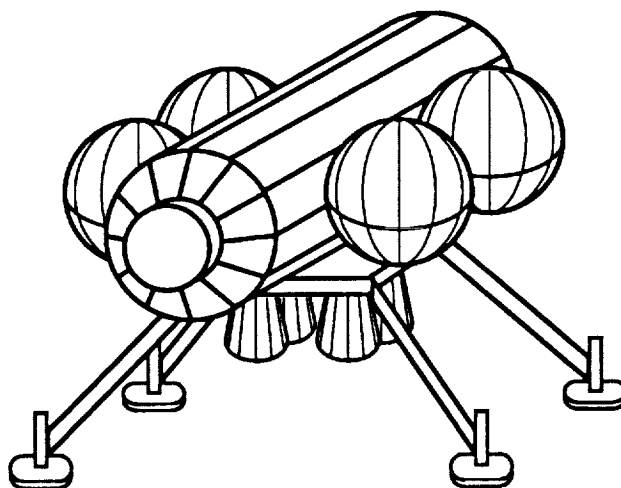


Figure 6: SADDLEBAGGED FUEL TANK  
CONFIGURATION

wider than those of the BC and MBC to accommodate attachments of both the cargo module and the fuel tanks.

### Saddlebagged Cargo Module Configuration

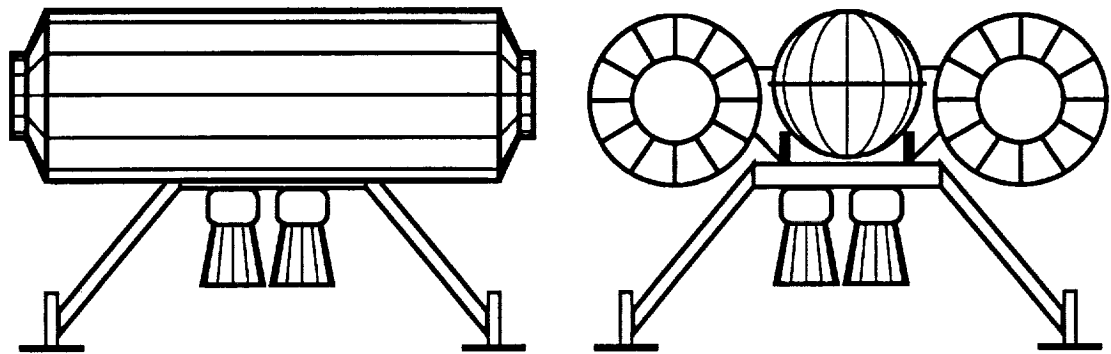
The Saddlebagged Cargo Module Configuration (SCMC) has one platform upon which two cargo modules are mounted on either side of a single row of fuel tanks (see Figure 7). It has the same advantages as the SFTC except that it has a large rotational moment of inertia due to the separation of the massive cargo modules from the center of gravity. Also, this configuration requires doubling fuel, engine power, and structural strength. Mass increases of this magnitude may be undesirable in some mission scenarios.

## POST-LANDING FUNCTIONS

The first part of this section presents possible uses of the lander structure as a whole and as parts. The parts of the structure are the legs, platform, and chassis. The second part of this section describes possible uses of the fuel tanks after landing.

### Lander Structure

By removing the fuel tanks, engines, and instrumentation, the entire lander structure can be arranged into a shelter for the habitation module (see Figure 8). If the structure is not initially tall enough to clear the cargo



Side View

Front View

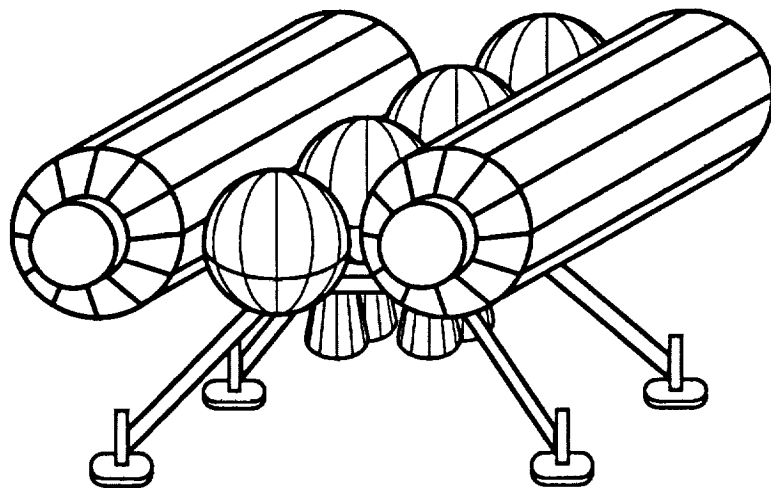


Figure 7: SADDLEBAGGED CARGO MODULE  
CONFIGURATION



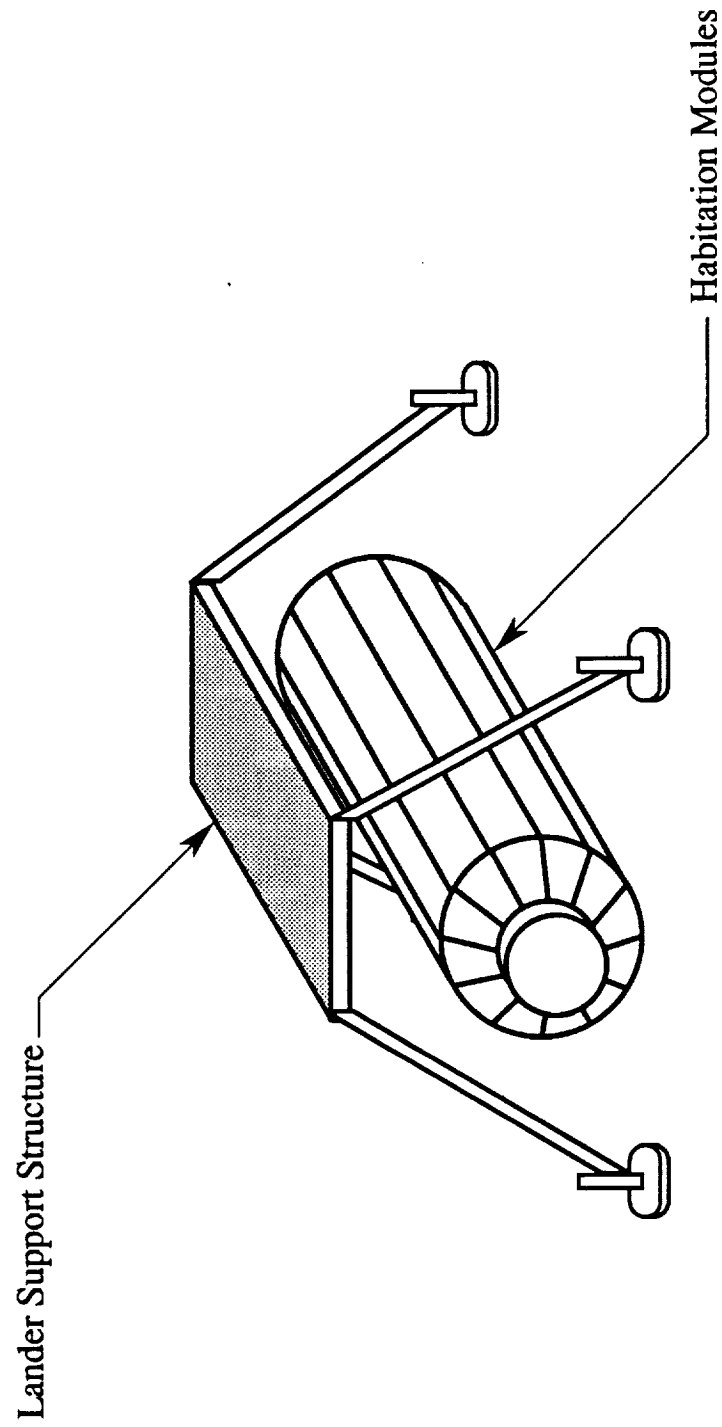


Figure 8: HABITATION MODULE SHELTER

module, then the legs could be designed to swing into a more vertical position until the desired height is attained.

The resulting shelter could be covered with regolith to provide the habitation module with sufficient radiation protection (see Figure 9). A continuous sheet of material must then cover the platform to prevent the regolith from falling through the structure. If not initially large enough, the platform could somehow expand to cover the entire habitation module.

The shelter concept can also be applied to the construction of garages for vehicles or any other equipment requiring protection. An advantage to keeping the landing structure intact is the elimination of the manpower needed to disassemble the structure into parts. Also, because this design requires no finished surfaces, the lander structure can tolerate some amount of damage due to landing impact and still serve this post-landing function.

Legs. The lander structure may also be disassembled into the legs, chassis, and platforms to perform other functions. The lander legs may be used as booms or stabilizers for the lunar lifting machine (see Figure 10). The strength and length of the legs is appropriate for this application. However, a major drawback is that not all the legs would be utilized as booms due to the limited number of lunar lifting machines needed. Also, if the legs need finished surfaces, they will require special protection from landing blast ejecta and micrometeorite damage. The landing blast projects

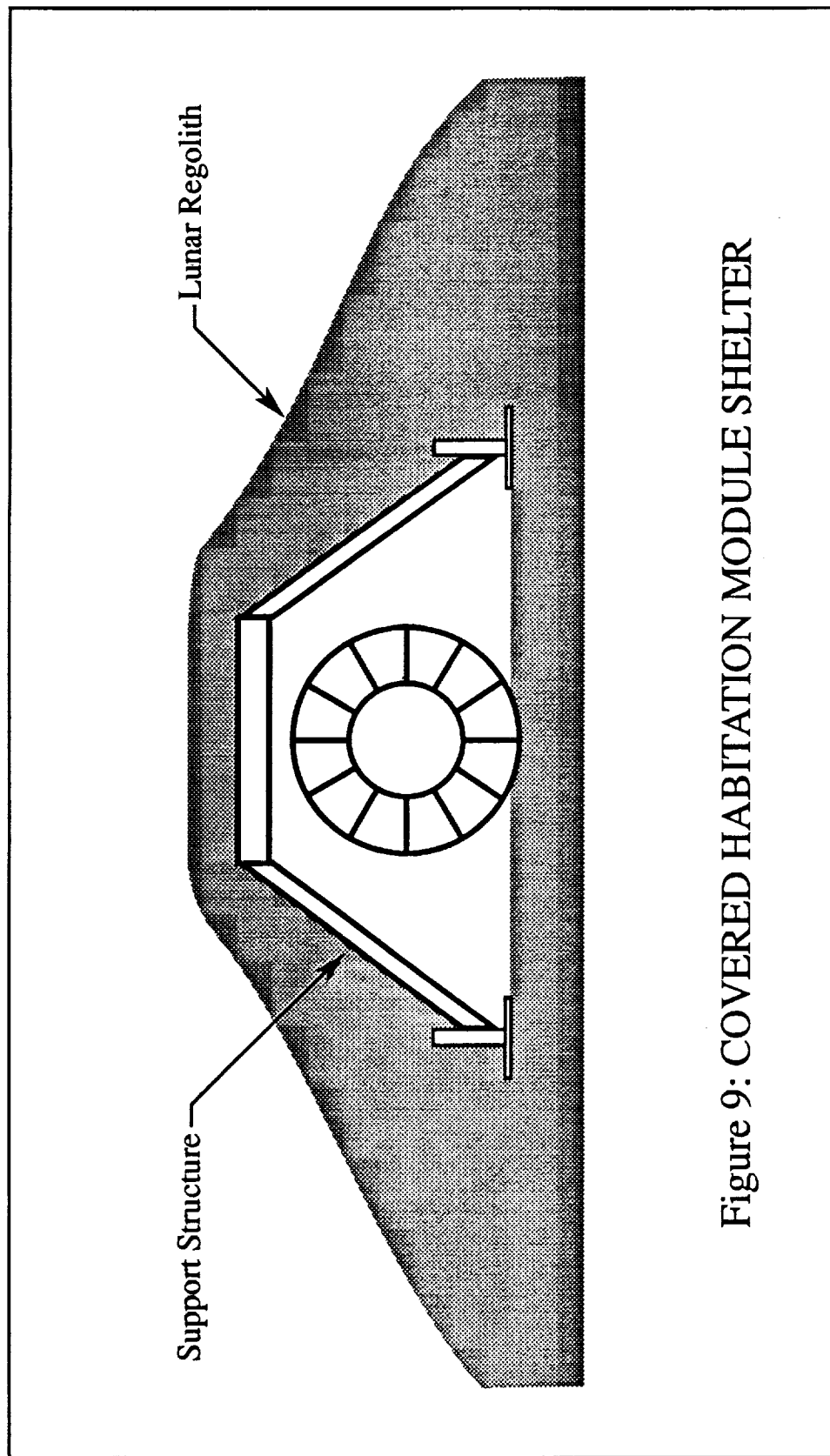
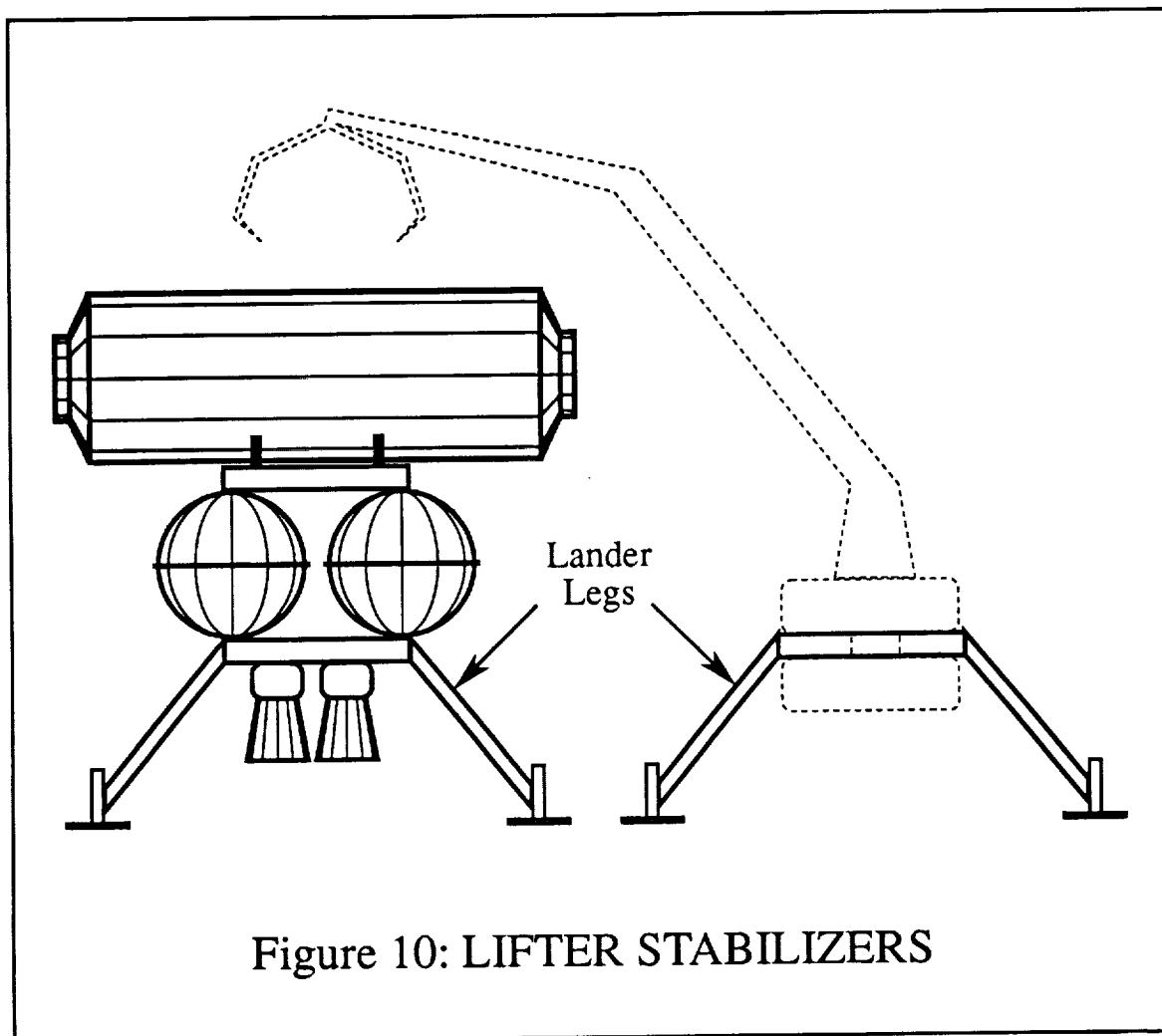


Figure 9: COVERED HABITATION MODULE SHELTER



lunar dust at high velocities and can damage finished surfaces up to 2 kilometers away [4].

The truss structure of the lander legs may be broken down into poles for antennae. Whether all of the lander legs would be utilized in this capacity depends on the need to elevate communication equipment. A disadvantage to this idea is that disassembling the legs to their base parts would require special tools and may be difficult for low-dexterity robots or crew in space suits.

The lander legs may also be converted into beams, rods, and trusses useful for constructing lunar structures. The lander legs are strong and lightweight and therefore appropriate for this purpose. However, a disadvantage to this idea is the time delay until building materials for complex structures will be needed at the lunar base.

Another idea is to use hollow lander legs as piping for the LUNOX plant. An advantage to this idea is that all the legs would be used. A major disadvantage to this idea is that it does not fulfill an immediate need, since a LUNOX plant will not be constructed until late in the lunar base development. Furthermore, the connecting ends of the pipes will be highly susceptible to damage during landing impact, especially if they are threaded.

The lander legs may be configured as rails or columns for a transport system. This function would be advantageous in that a transport system is desired early in the lunar base scenario and all the legs would be used. Also, the transport system would benefit from the strength of the

lander legs. A disadvantage is that rails will need straight finished surfaces requiring special protection during landing.

Finally, the lander legs can be used as tubing or conduit for electrical cable. As for piping, the legs must be hollow. Disassembled, the lander legs would provide variable lengths and appropriate quantities of conduit. A disadvantage is that the strength of the legs will not be utilized.

Chassis. The lander chassis connects the fuel tanks, platforms, engines, and instrumentation systems together and is exclusive of the leg structure. It is less constrained than the other components in shape and orientation. Like the lander legs, it will probably consist of an efficient truss design and therefore have possible uses similar to those of the lander legs.

The chassis could be used as a framework to hold the tanks together for easy handling by a lifting machine (see Figure 11). This design would be advantageous for protection and transportation. However, it may be impractical for the lifter to handle all the tanks at once and inefficient for permanent storage.

Another possible chassis design would facilitate lowering the cargo platform down to the engine platform after the fuel tanks have been removed (see Figure 12). Lowering the cargo platform simplifies removing the cargo module. A disadvantage to this design is that it serves a one-time function and therefore constitutes a waste of material.

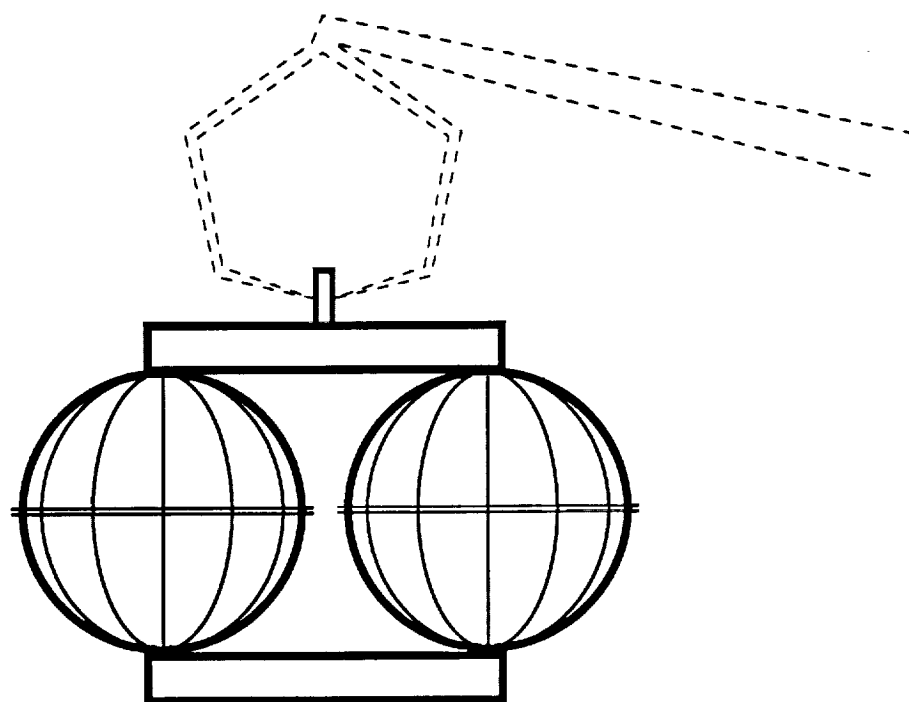
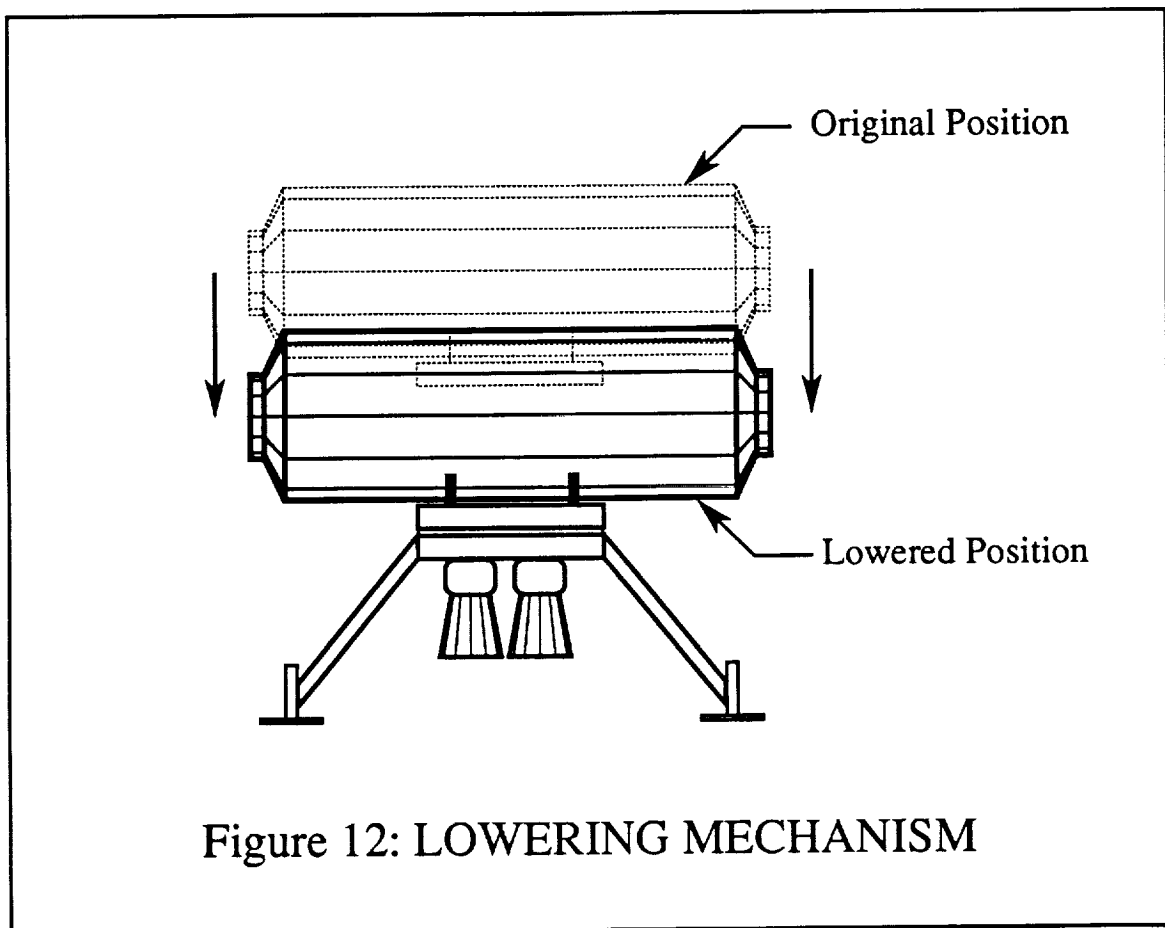


Figure 11: FUEL TANK CONTAINER





Platform. The lander platforms are integral structures upon which the cargo module, fuel tanks, legs, engines, and instrumentation are mounted. The design team is not restricted to the number of these platforms.

After the lander has landed, the platforms may be used wholly or partially as blades for construction purposes such as levelling or excavation (see Figure 13). This design is advantageous in that it meets an immediate construction need for establishing the lunar base. However, not all the platforms may be used since the number of excavating machines may be small. Another disadvantage would be a mass penalty to the lunar lander due to the durability requirements for heavy construction equipment.

One possible use that would utilize all the platforms is to interlock them to form a sizeable landing surface for future landings or a floor for a garage or work area. However, this design would probably not be useful until reusable landers are employed after the preliminary base has been established.

### Fuel Tanks

The fuel tanks hold fuel for the lander descent and residual fuel after landing. The design team anticipates each lander having spherical tanks, which can be arranged within truss structures or fitted about the cargo module.

One use for the tanks after landing is to keep them as storage tanks for the lunar base. This would meet immediate needs of the lunar base and

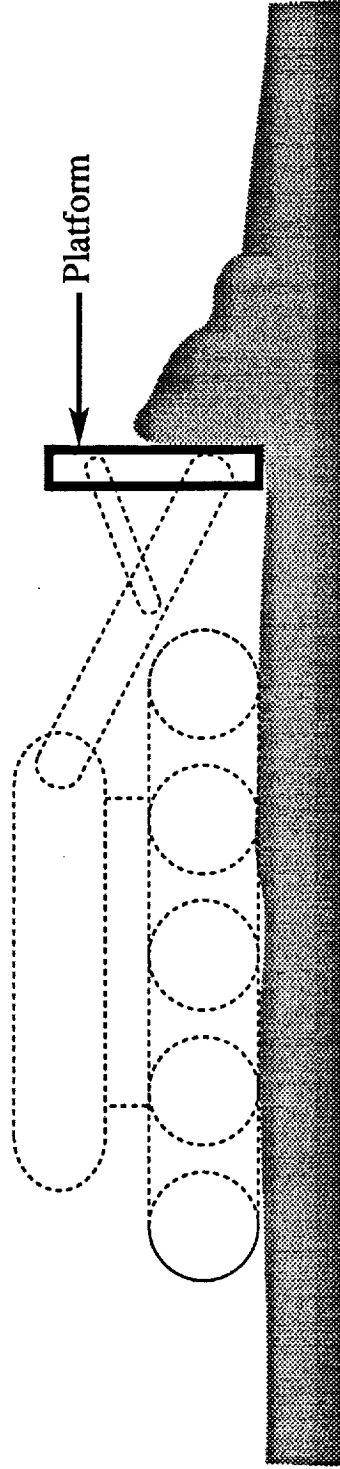


Figure 13: EXCAVATING BLADE

would require no transformation, merely relocation. Furthermore, the tanks would be employed as they were originally designed. Eventually all the tanks would be used. However, they would need to be cleaned and physically and thermally protected from the harsh lunar environment. Protection could be accomplished by burying them under the lunar surface.

Another possible use for the tanks is as spherical or hemispherical wheels for a construction or transportation vehicle (see Figure 14). A disadvantage to this idea is that a process would have to be developed to attach the wheels to an axle. Furthermore, if hemispherical wheels are used, the tanks would have to be designed to be halved on the lunar surface. Also, the vessel capabilities of the tanks would be wasted.

Assuming that the lander has four tanks, it could be equipped in such a way that it could lower itself down upon the tanks and use them as large ball-bearing rollers upon which it could be towed (see Figure 15). Such a vehicle would have omni-directional rolling capabilities. However, lunar dust and a vacuum environment would cause lubrication and friction problems within the rolling mechanism. Again the vessel capabilities of the tanks would be wasted.

## SUMMARY

In this chapter, the design team has presented alternate designs for the overall lander configuration and for the post-landing functions of its components. The lander components considered for post-landing uses were the fuel tanks and the structure, which consists of the legs, chassis, and

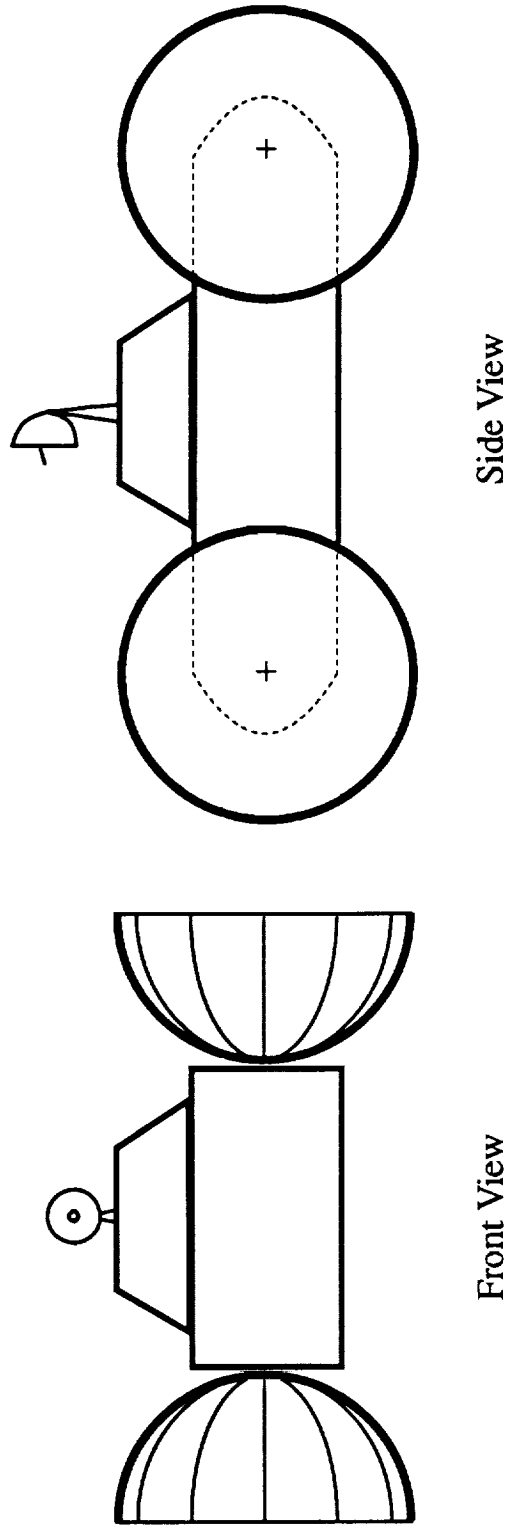


Figure 14: WHEELED VEHICLE

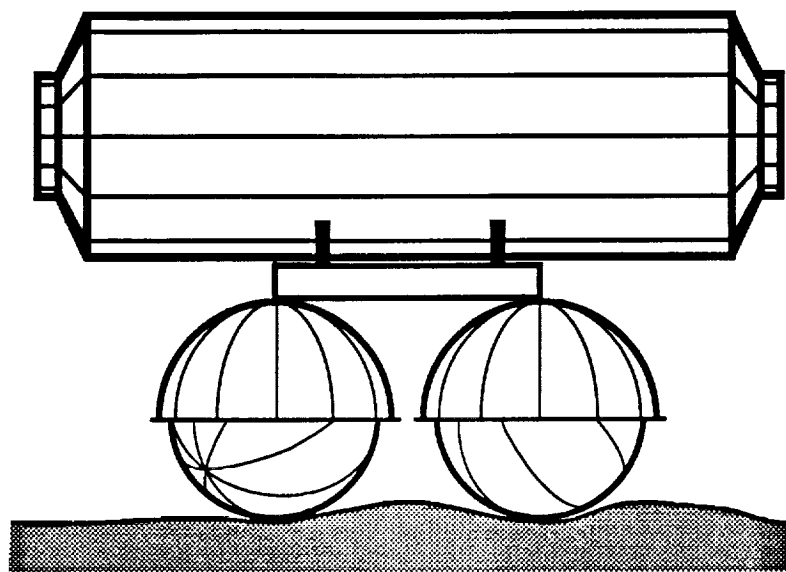


Figure 15: ROLLER VEHICLE

platform. Advantages and disadvantages of each design were discussed in the context of objectives and criteria defined by the team.

From these alternate designs the team selected a final design using decision matrices. The next chapter describes the chosen overall lander configuration and post-landing functions.

## DESIGN SOLUTION

The design solution consists of a lander employing the Saddlebagged Fuel Tank Configuration (see Figures 16, 17). After landing, the lander will provide a habitation module shelter, storage tanks for liquids on the base, and engines and instrumentation for stock parts. The design solution was chosen based on the two decision matrices given in Appendix A. The first matrix involved the overall lander configurations. The second matrix involved the post-landing functions of the lander components.

### OVERALL LANDER CONFIGURATION

The Saddlebagged Fuel Tank Configuration provides an effective arrangement for the safe transport and easy unloading of cargo. The SFTC was chosen primarily because of its low center of gravity, low rotational moment of inertia, and the accessibility it provides to the fuel tanks and cargo module. Also, the large size of the platform is ideal for a habitation module shelter, the chosen post-landing function of the lander structure.

### Lander Dimensions

The lander dimensions are shown in Figures 18 and 19. Arranging the lander components in this way gives the center of mass of the vehicle a height of approximately 7 meters. With this relatively low center of gravity the lander can maintain a tilt of  $36^\circ$  without tipping. Calculations for the location of the center of gravity and the maximum angle of tilt are given in Appendix B. Furthermore, the size of the platform gives the

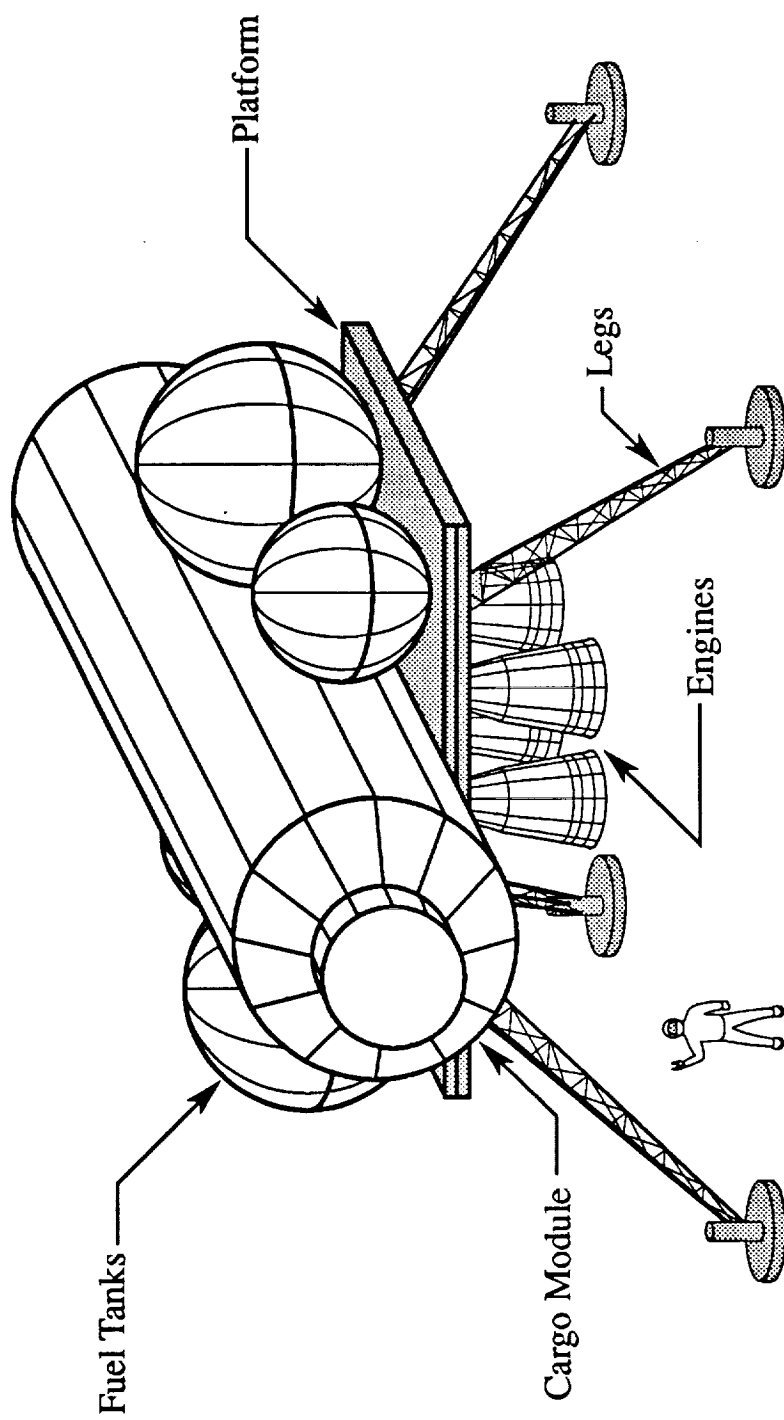


Figure 16: OVERALL VIEW OF SADDLEBAGGED  
FUEL TANK CONFIGURATION



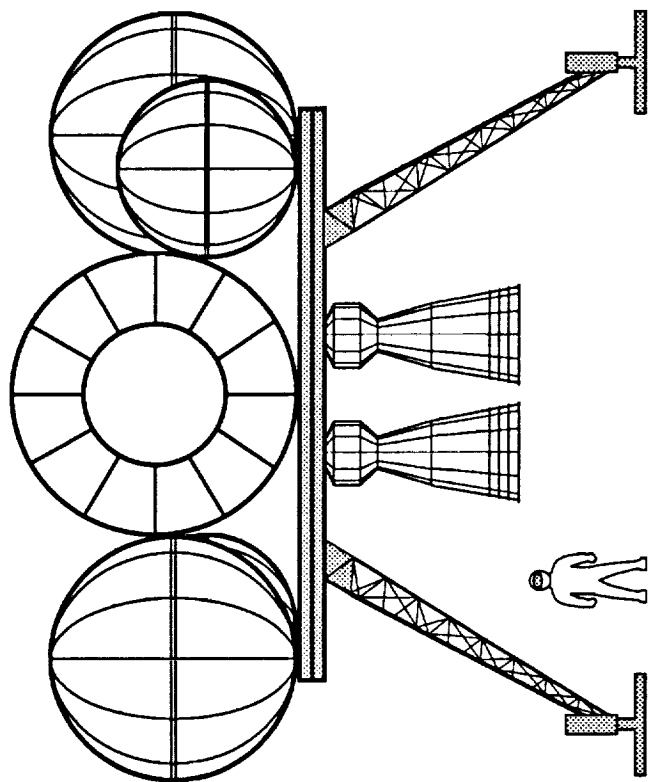


Figure 17: FRONT ELEVATION OF SADDLEBAGGED  
FUEL TANK CONFIGURATION

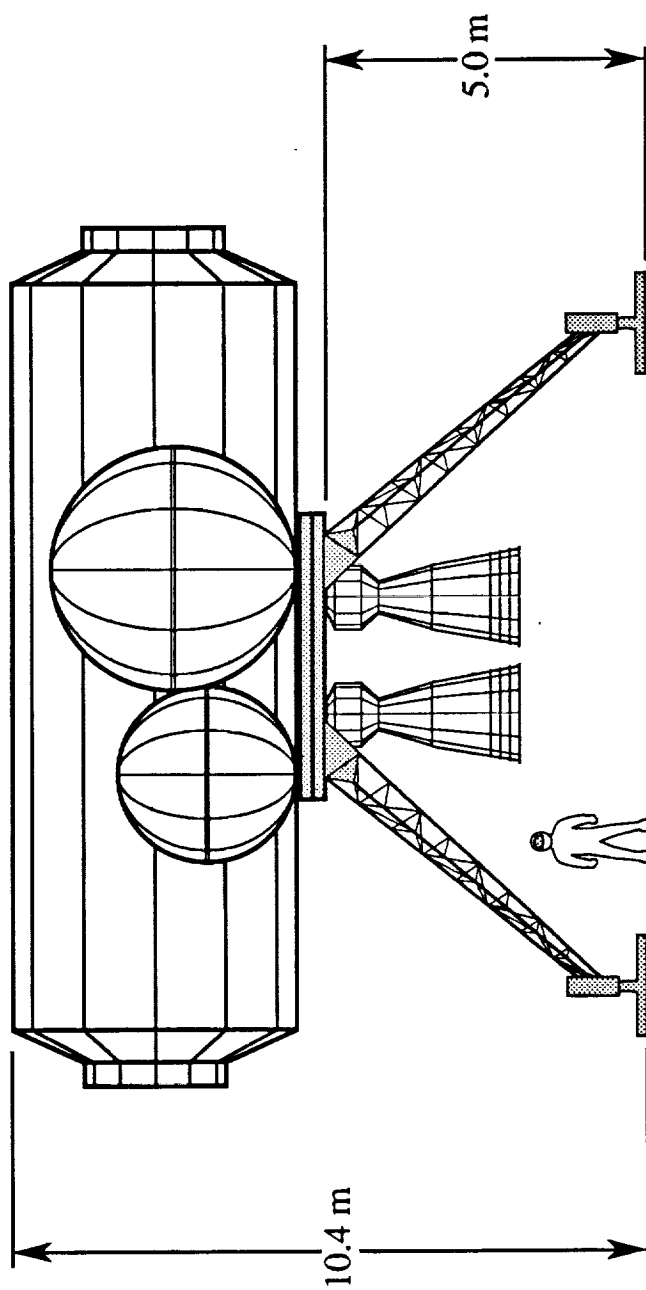


Figure 18: SIDE ELEVATION OF SADDLEBAGGED  
FUEL TANK CONFIGURATION

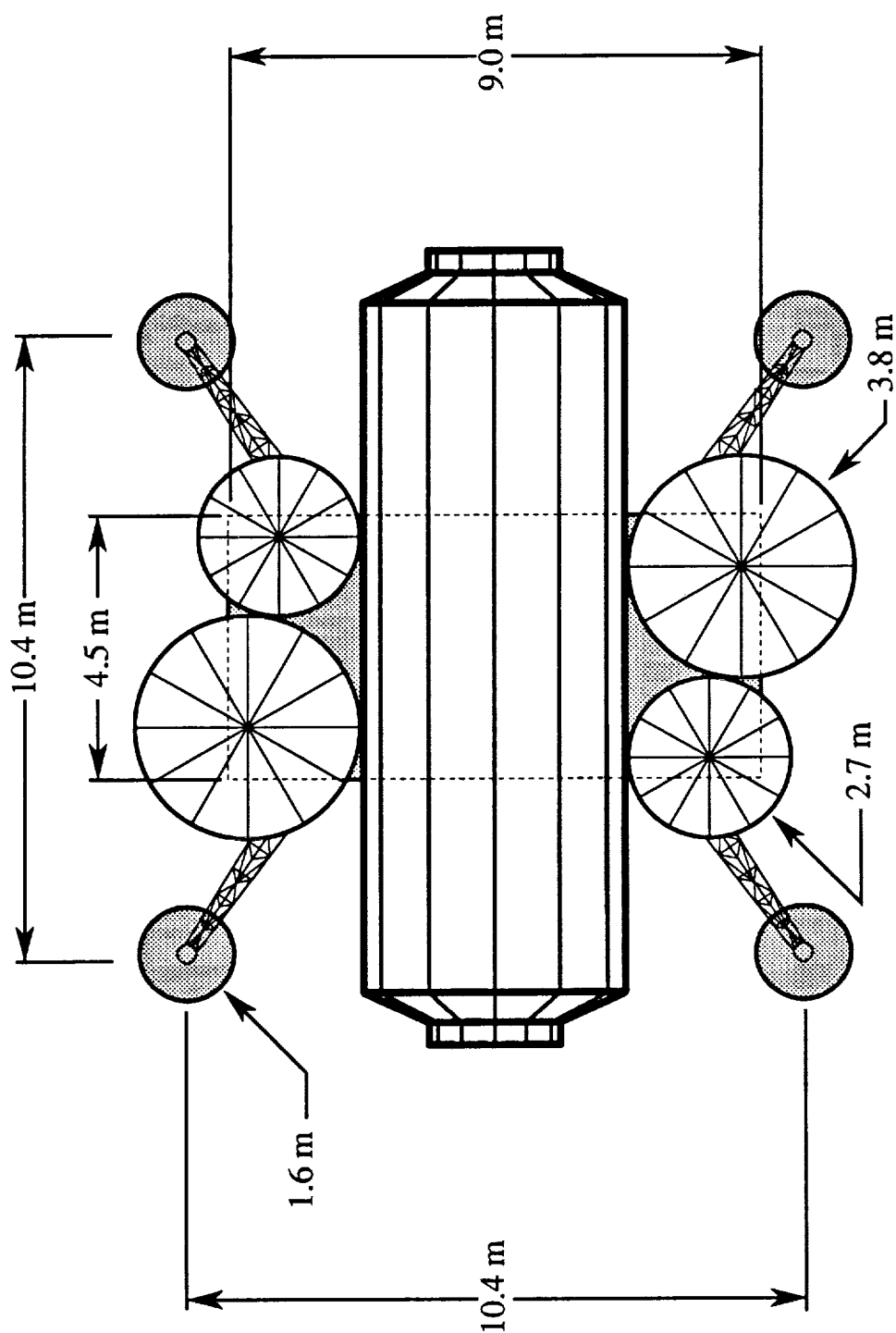


Figure 19: TOP ELEVATION OF SADDLEBAGGED FUEL TANK CONFIGURATION

cargo module sufficient support to safely withstand landing impact. Calculations of impact forces on the cargo module are given in Appendix F.

### Lander Mass

The total mass of the cargo-laden lander without propellant will be a maximum of 36,600 kg. A summary of the lander mass is provided in Appendix E. Most of the mass estimates were based on an Eagle Engineering report of a lunar lander conceptual design [1]. However, because of configurational differences, the design team made its own estimates of the lander structure mass. These estimates were accomplished in conjunction with an impact stress analysis as shown in Appendix C.

A major consideration in the design of the legs and platform were the structural stresses produced by the landing impact. Bending stresses pose the greatest threat of structural failure. To perform a stress analysis, the lander structure was modeled by a minimum number of intersecting I-beams. The following assumptions were made for the analysis:

1. The lander engines will be shut off at a height of 3 meters above the lunar surface. This distance is the approximate height from which the Apollo landers dropped during landing.
2. Three decimeters vertical deformation of honeycomb aluminum will cushion the landing impact to a constant deceleration of 10 lunar g's ( $16.3 \text{ m/s}^2$ ).
3. The lander structure is made of high-strength 7075 Aluminum Alloy.

Using a safety factor of five, commonly used by NASA, the design team calculated the section moduli necessary for the legs and platform to prevent plastic deformation upon impact. Appropriately sized I-beams were selected to achieve these moduli and respective masses were calculated. These mass values represent estimates of the upper limit of the lander structure mass since less massive truss or honeycomb structures can be designed to achieve the same section moduli.

### POST-LANDING FUNCTIONS

The post-landing functions of the lander components were chosen because they best constitute a complete and versatile use of the lander material, they fulfill an immediate need of the lunar base, and they require only simple transformations. The habitation module shelter will support a protective layer of regolith and the fuel tanks will contain cryogenic liquids or aqueous solutions for the lunar base. The engines and instrumentation will be detached and saved as stock parts for future reusable landers.

#### Habitation Module Shelter

In the present lunar base scenarios, cargo landers will precede manned landers by 6 to 12 months. When the manned lander arrives, the crew will perform a number of simple steps to transform the lander structure into a habitation module shelter.

Fuel Tanks, Engines, and Instrumentation Removed. A lifting machine must first remove fuel tanks, engines, and instrumentation to access the cargo module and lander structure (see Figure 20). Each of these components, as well as the cargo module, will be equipped with quick release mechanisms to simplify their removal.

Habitation Site Prepared. The cargo modules will be converted into habitation modules once they are emptied of their cargo. Therefore, a habitation site must be prepared to accommodate the habitation module. The habitation site consists of a shallow trench, approximately 0.4 meters deep, lined with regolith-filled bags. The purpose of the site is to provide a stable foundation for the module and make the module entrance more accessible from ground level.

Cargo Module Removed and Positioned. After the habitation site has been prepared the cargo module will be removed from the lander platform and laid in its proper position by the lifting machine. From this position the cargo module can readily be unloaded.

Shelter Positioned. After removing the cargo module and the other lander components, the only remaining part of the lander is the structure. The lander structure will be lifted over the habitation module and set down in a symmetrically centered position. The lengthwise dimension of the lander structure platform will be covering the lengthwise

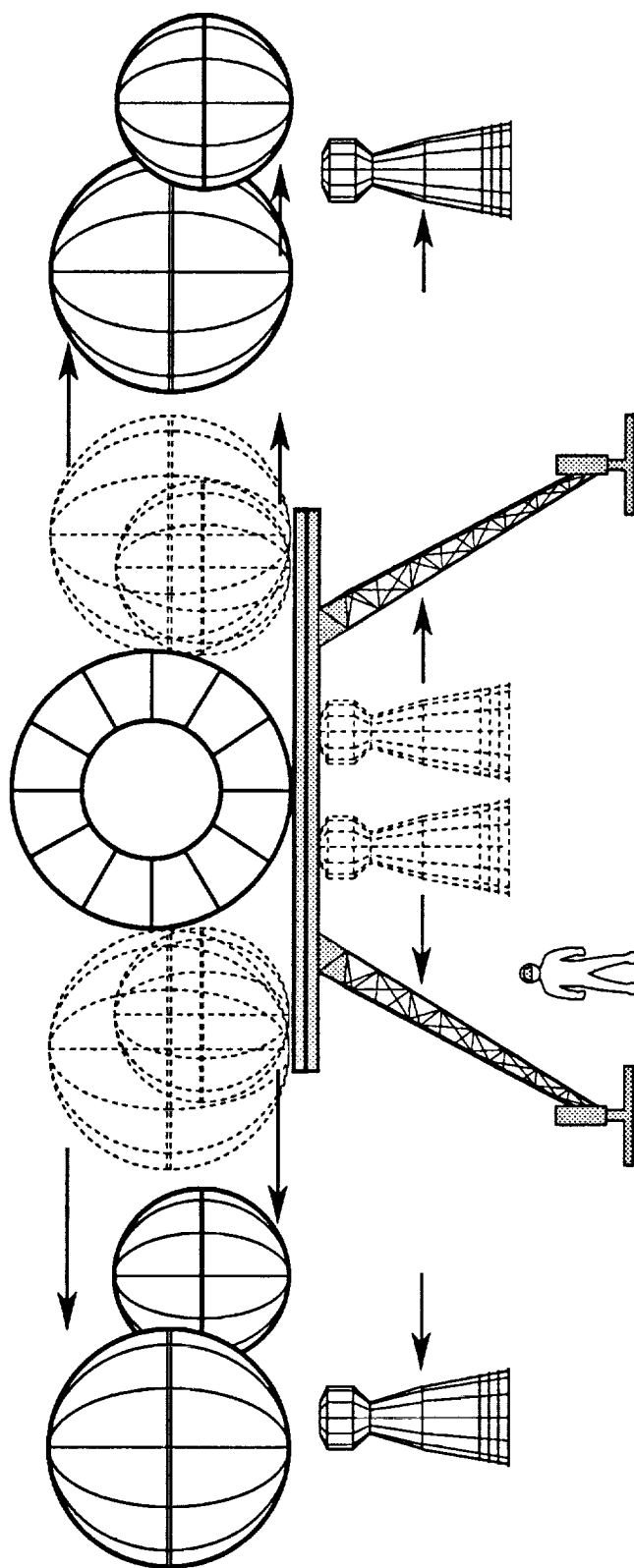


Figure 20: FUEL TANKS AND ENGINES REMOVED

dimension of the habitation module. In this position it will straddle the module with a minimum clearance of one meter (see Figure 21).

Platform Unfolded. The lander structure platform consists of two layers that are hinged on either end and folded together. The top layer of the platform is unfolded to cover the entire length of the habitation module with 2.25 meters of overhang on either end (see Figure 22).

Folding Lattice Positioned. To support the sides of the habitation shelter, a light-weight folding lattice structure can be anchored in the lunar soil next to the footpads and leaned against the platform. This structure will be transported with the other cargo in the cargo module in a folded-up position and will be unfolded to extend the length of the habitation shelter on the lunar surface (see Figure 23).

Entrances Prepared. Protection for the ends of the habitation shelter will be provided with walls of regolith-filled bags. These walls will add support to the covering layer of regolith and can be arranged to make an entrance way. By curving or cornering the entrance, radiation protection can be maintained while providing a direct route between the inside and outside of the sheltered area.

Shelter Covered. The final step in constructing the habitation shelter is to cover the lander structure with regolith. To keep the regolith from



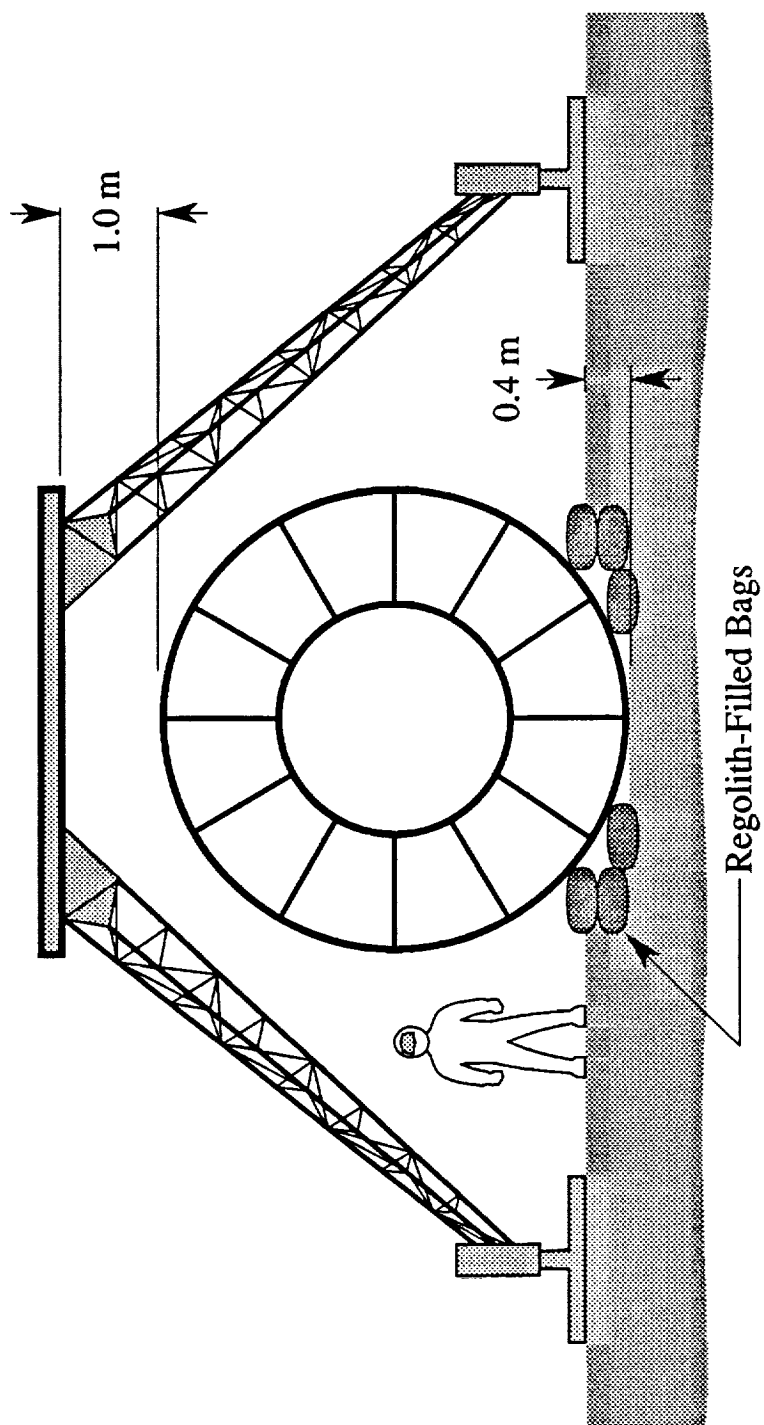


Figure 21: SHELTER POSITIONED OVER  
HABITATION MODULE

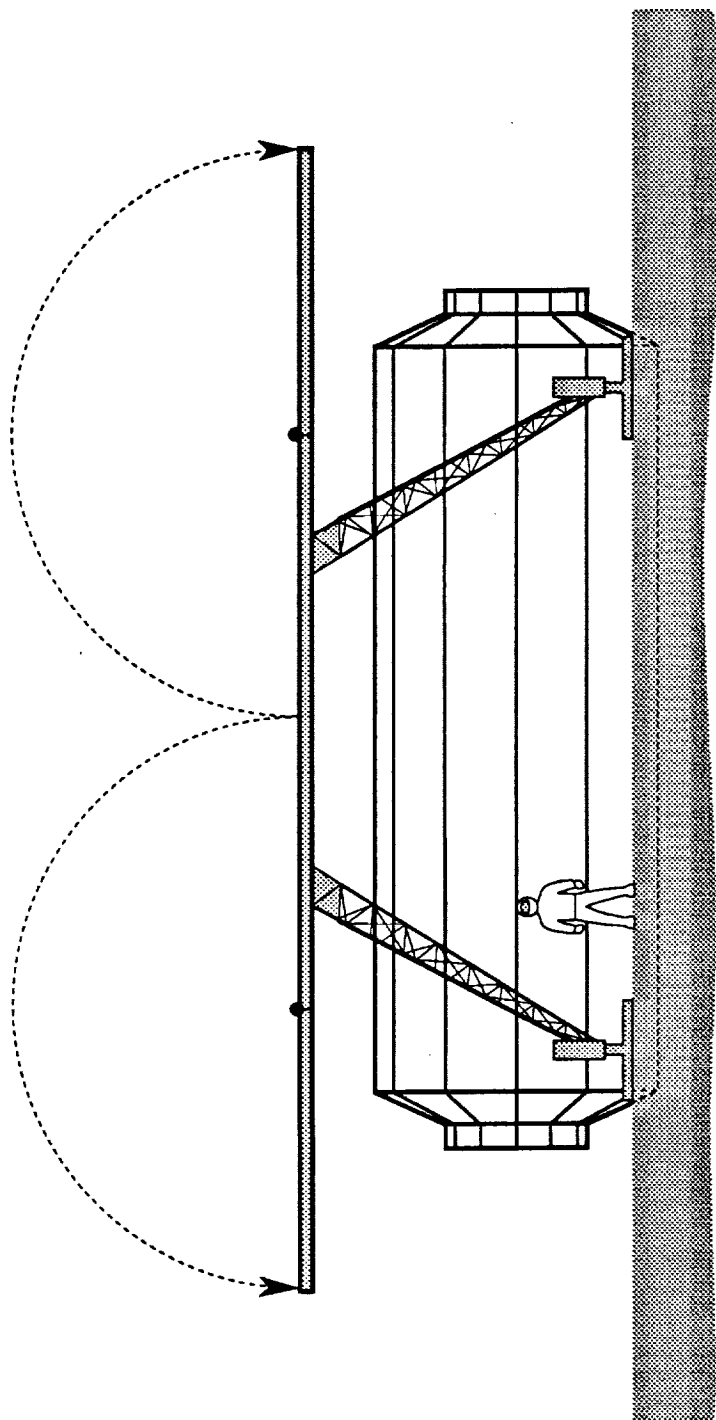


Figure 22: UNFOLDING PLATFORM

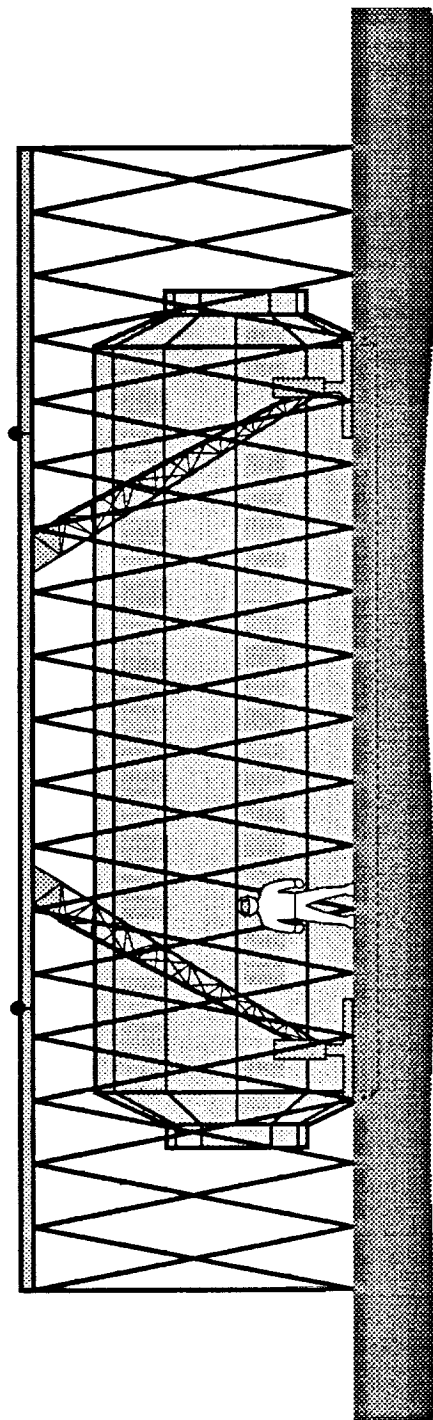


Figure 23: FOLDING LATTICE ATTACHED TO  
HABITATION SHELTER

sifting through the platform and lattice supports, a high tensile strength material will be stretched over the entire shelter structure. This material may be the same material used to protect the lander during its 6 to 12 month wait for the following manned lander. However, the material must withstand a regolith pressure of 13.5 kilopascals, as calculated in Appendix G.

When all components of the shelter are in place, the entire shelter is covered with a layer of regolith, 2 meters thick at the top (see Figure 24) [3]. The results of calculations given in Appendix D indicate that the platform deflects a maximum of 4 centimeters, which is insignificant compared to the one meter clearance above the module. Therefore additional supporting poles will not be necessary. A summary of platform deflections due to regolith loading is given in Appendix E.

Shelters Multiplexed. One of the benefits of the habitation shelter design is its versatility in multiplexing. Just as one shelter can accommodate one habitation module, any number of shelters can be linked in series to protect a chain of adjoining habitation modules (see Figure 25). To connect the platforms of two shelters, the ends of each platform are equipped with bevelled teeth which mesh together (see Figure 26). A hole in each tooth allows a long pin to be inserted through the teeth to effect a revolute joint. In the same way, the platform will be locked in its folded position during flight.

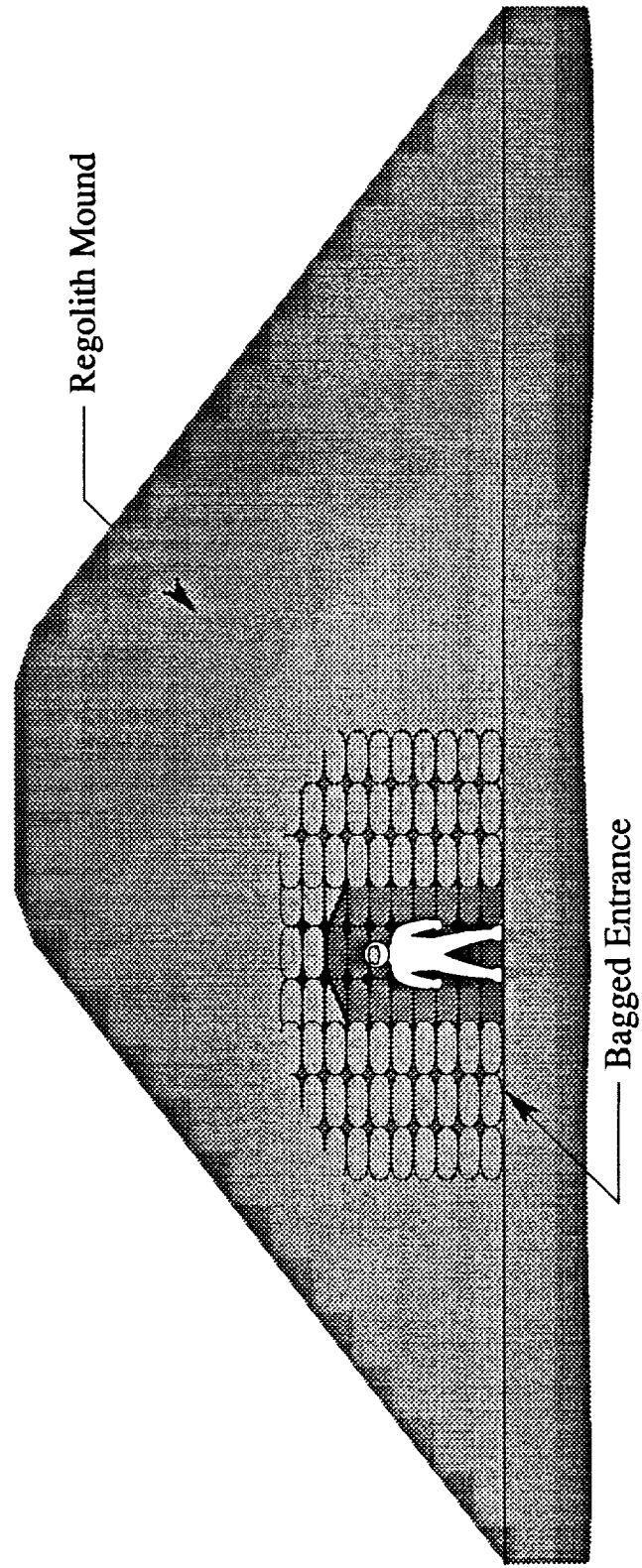


Figure 24: COMPLETED HABITATION SHELTER

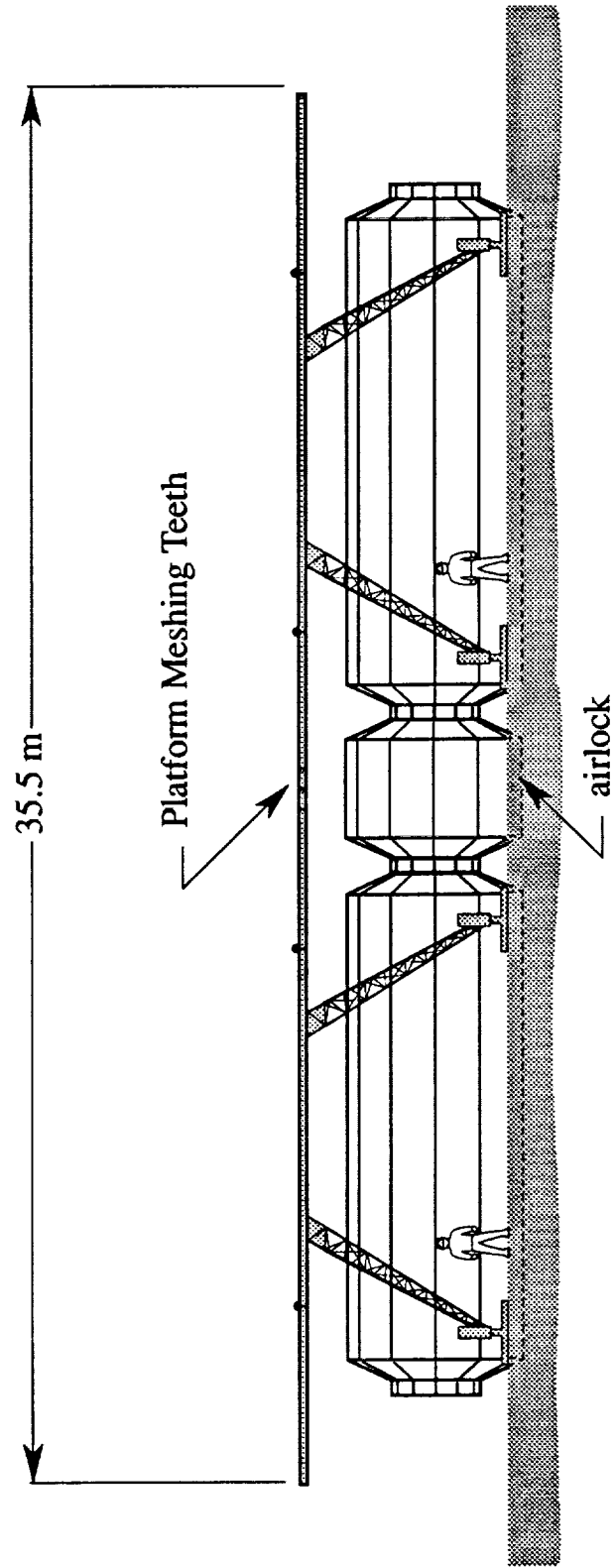


Figure 25: MULTIPLEXED HABITATION SHELTERS

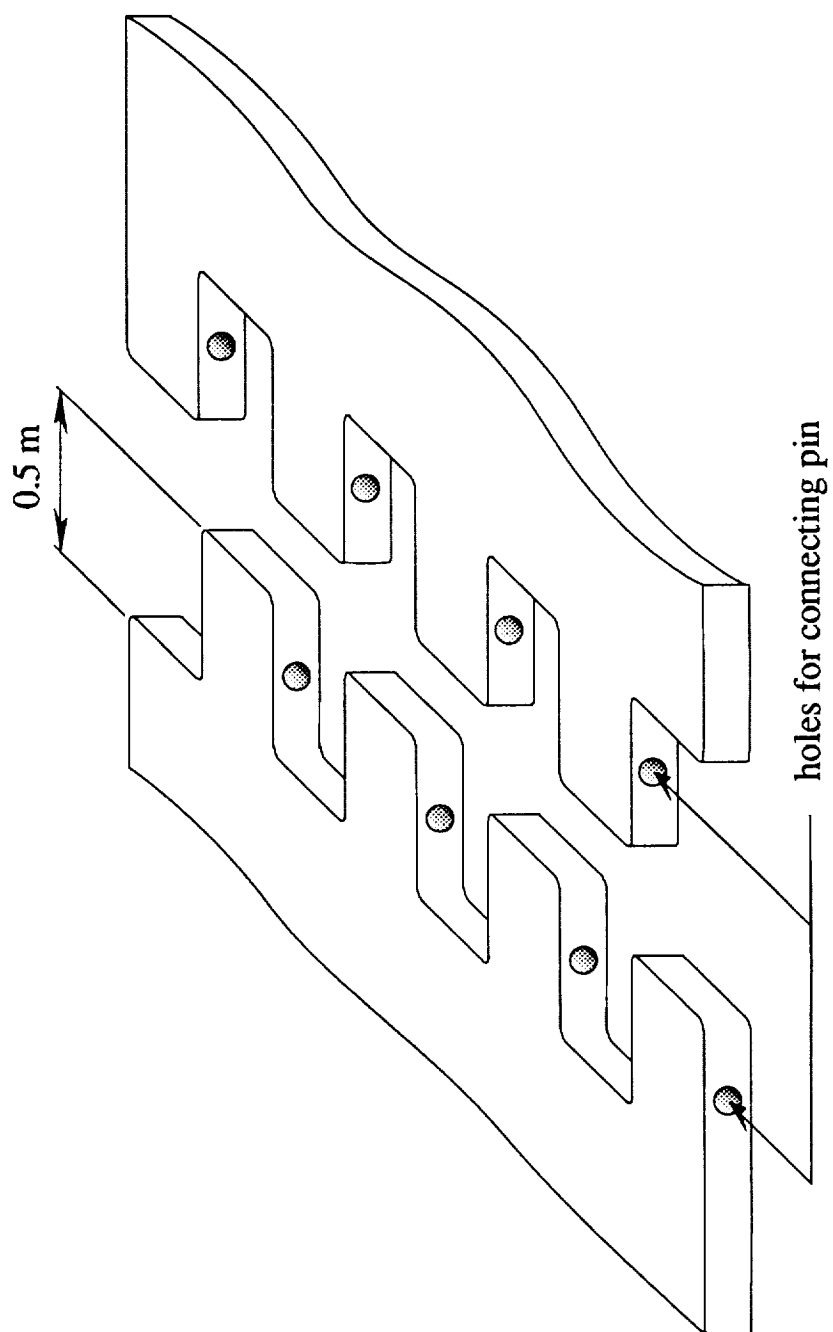


Figure 26: PLATFORM MESHING TEETH

Benefits Derived. The constructed habitation shelter provides a number of benefits for the lunar base, most of which derive from the fact that this design avoids the necessity of burying the habitation module. One benefit is that astronauts in extra-vehicular activity (EVA) suits have access to the exterior of the habitation module to perform any necessary maintenance. Additionally, this exterior space may be used as a protected storage area.

Another benefit is that the shelter protects the thin-walled module from the pressure superimposed by the regolith covering. This pressure has been estimated to be in excess of 5 kilopascals [3].

### Storage Tanks

The lander will require no more than 4000 kilograms of liquid hydrogen and 24000 kilograms of liquid oxygen. These fuels are most efficiently stored in two pairs of spherical tanks, one pair for each fuel, to allow symmetrical loading of the vehicle and to minimize total tank mass. The tanks of similar fuels are attached diagonally opposite each other on either side of the cargo module in the Saddlebagged Fuel Tank Configuration.

Upon landing, the fuel tanks will contain a residual amount of fuel. After removal of the tanks, each residual fuel will be consolidated into one tank. The emptied tanks will then be cleaned and used to store fuels, oxygen, and water. For cryogenic storage, the tanks can be buried under lunar regolith near the habitation site.



### Stock Parts

Although the lander being designed is not intended for re-launch, scenarios for the permanent lunar base call for the eventual re-launching of cargo from the lunar surface into low lunar orbit. Therefore, the design team assumes that technology will provide engines capable of re-firing and that the engines mounted on the initial landers will have that capability.

To prepare for future re-launching, the engines and instrumentation will be removed from the lander by a lifting machine and stored on the lunar surface, perhaps in a garage structure. There, they will be saved as stock parts for reusable landers later in the lunar base development.

## CONCLUSIONS AND RECOMMENDATIONS

The final design solution successfully meets the first project requirement, to design an unmanned lunar cargo lander that both safely lands cargo on the moon and performs a post-landing function useful to a permanent manned lunar base. The second project requirement, to construct a demonstration model, was also successfully accomplished.

The final design employs a Saddlebagged Fuel Tank Configuration, which provides a stable arrangement of the lander components and payload for the safe transport of cargo from low earth orbit to the lunar surface. The configuration also facilitates the removal of the cargo module by having the module on one low platform next to the fuel tanks.

The cargo lander can be simply transformed with a minimum of EVA time. The lander structure will be converted into a habitation module shelter that will support a 2-meter thick layer of regolith, which provides protection from harmful radiation. The fuel tanks will be reused as tanks for storage of fuel, oxygen, and water on the base. The engines and instrumentation will simply be detached and saved as stock parts for future reusable landers.

These post-landing functions constitute a versatile use of the entire lander structure. Furthermore, the habitation module shelter and storage tanks fulfill an immediate need of the lunar base for radiation protection and conservation of liquids. Not only is the habitation module shelter design beneficial for a large lunar base, but also it is ideal for the establishment of a remote lunar outpost.

The team makes the following recommendations for future development of the design:

1. Investigation of quick-release mounts that will securely hold the cargo module, fuel tanks, engines, and instrumentation during flight. These mounts should be easily unlatched to reduce EVA time during unloading of the lander.
2. Development of energy-saving systems that can store the potential energy released by lowering of cargo or kinetic energy released during impact. The stored energy could be used to pressurize a pneumatic vessel, which could later be used to power pneumatic tools or deploy an inflatable protection system.
3. Research into the possibility of using state-of-the-art materials such as fiber reinforced composites to reduce the mass of the lander while retaining its structural strength.
4. Development of simple tank-cleaning techniques and facilities for efficient transformation of fuel tanks into multi-purpose storage tanks.
5. Development of electro-mechanical or fluid energy-absorption systems capable of operating effectively in the vacuum environment of the moon. These systems will eliminate the need for sacrificial impact-absorption members that might deform non-uniformly about the lander, resulting in a lop-sided habitation module shelter.
6. Conduction of detailed impact analyses using data obtained from future landings. The results will enable future lander design teams to better reduce impact forces, thereby minimizing the necessary section moduli and mass of the lander structure.

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2. Guerra, Lisa Ann, "A Commonality Assessment of Lunar Surface Habitation," (Department of Aerospace Engineering, The University of Texas at Austin, Thesis for a Master of Science in Engineering), p. 24.
3. Kaplicky, Jan and David Nixon, "A Surface-Assembled Superstructure Envelope System to Support Regolith Mass-Shielding for an Initial-Operational-Capability Lunar Base," Lunar Bases and Space Activities of the 21st Century. (W. W. Mendell, ed., 1st ed., Lunar and Planetary Institute, 1985), p. 376.
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## **APPENDIX A**

### **DECISION MATRICES**

DESIGN CONSIDERATIONS → WEIGHTING FACTORS → LANDERS	DESIGN PARAMETERS							SUM OF PRODUCTS
	LOW CENTER OF GRAVITY	EASILY TRANS- FORMED	LOW MOMENT OF INERTIA	VERSA- FILE CARGO PAYLOAD				
	0.2	0.4	0.3	0.1				1.0
	7 1.4	6 2.4	6 1.8	10 1.0				6.6
	6 1.2	7 2.8	5 1.5	10 1.0				6.5
	10 2.0	9 3.6	7 2.1	6 0.6				8.3
	10 2.0	9 3.6	10 3.0	7 0.7				9.3



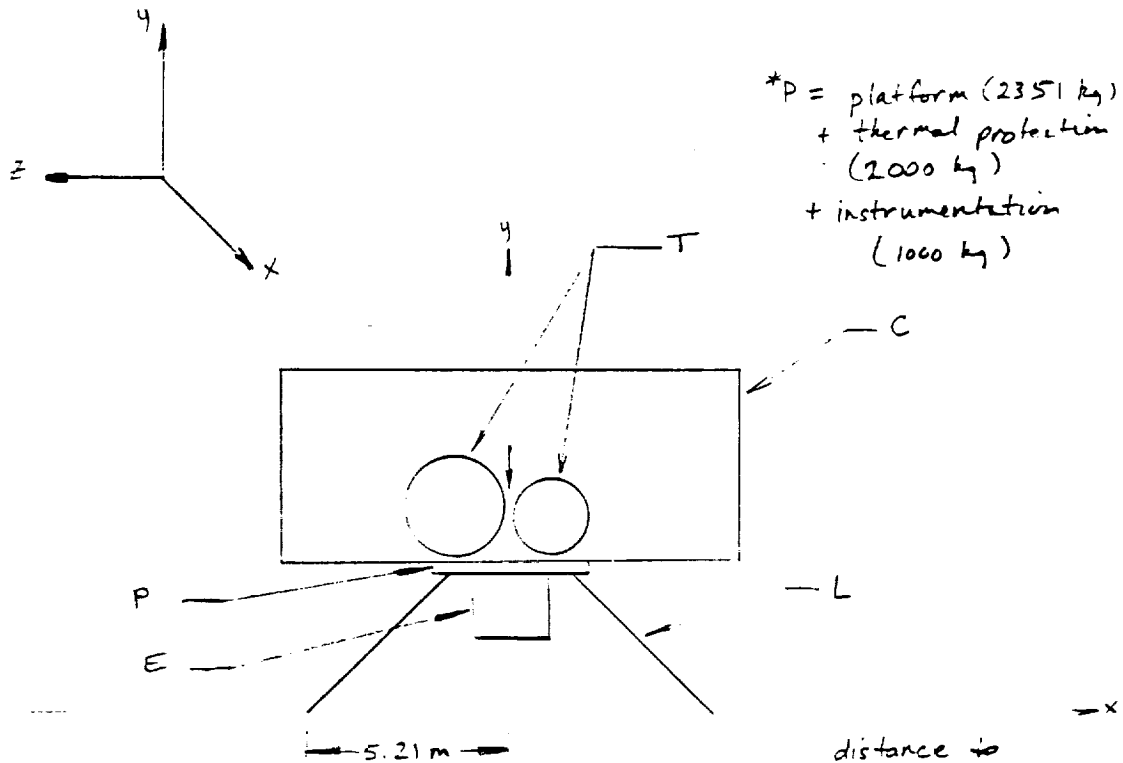
DESIGN PARAMETERS							
DESIGN CONSIDERATIONS → WEIGHTING FACTORS → USES	EARLY USE	FULL USE	SIMPLE TO IMPLE- MENT	HIGH TOLER- ANCE	HIGH VERSA- TILITY		SUM OF PRODUCTS
	0.1	0.4	0.1	0.1	0.3		1.0
	10 1.0	10 4.0	9 0.9	10 1.0	7 2.1		9.0
HABITATION SHELTER							
COMPONENT FUNCTIONS	6 0.6	10 4.0	4 0.4	5 0.5	10 3.0		8.5

## **APPENDIX B**

### **TILT CALCULATIONS**

# TILT

B1



\*P = platform (2351 kg)  
+ thermal protection  
(2000 kg)  
+ instrumentation  
(1000 kg)

T  $\equiv$  mass of tanks  $\approx 3,000$  kg  
C  $\equiv$  mass of cargo pod  $\approx 25,000$  kg  
L  $\equiv$  mass of legs  $\approx 1784$  kg  
\*P  $\equiv$  mass of platform  $\approx 5351$  kg  
E  $\equiv$  mass of engines  $\approx 1000$  kg

distance to  
centroid

$y_T \approx 7.0$  m  
 $y_C \approx 7.7$  m  
 $y_L \approx 2.5$  m  
 $y_P \approx 5.5$  m  
 $y_E \approx 4.0$  m

total mass = 36135 kg

$$y_{cm} = (T y_T + C y_C + L y_L + P y_P + E y_E) / 36,135 \text{ kg} = 6.957 \text{ m}$$

$$\text{Maximum tilt angle about z-axis} = \tan^{-1} \left( \frac{5.21}{6.957} \right) = 36.9^\circ$$

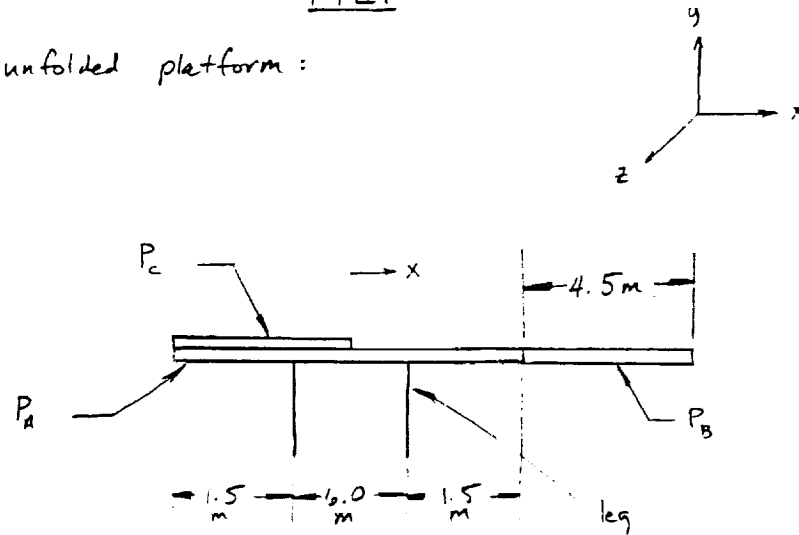
$$\text{Maximum tilt angle about x-axis} = \tan^{-1} \left( \frac{5.21}{6.96} \right) = 36.8^\circ$$

Appendix E gives all masses.

## TILT

B2

Half unfolded platform:



$P_A \equiv$  mass of this part of the total platform = 1175.5 kg

$P_B = 587.75 \text{ kg}$

TOTAL mass = 2351 kg

$P_C = 587.75 \text{ kg}$

centroids

$$x_A = 0$$

$$x_B = 6.75 \text{ m}$$

$$x_C = -2.25 \text{ m}$$

$$x_{cm} = (P_A x_A + P_B x_B + P_C x_C) / 2351 \text{ kg} = 1.125 \text{ m}$$

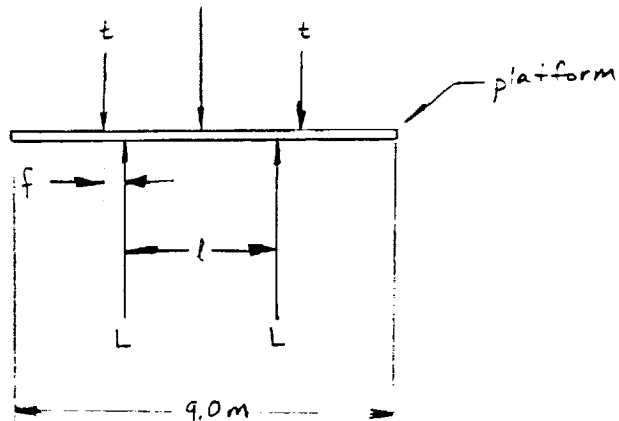
$\therefore$  The center of mass is shifted 1.125 m to the right, therefore the legs prevent the lander from tipping.

## **APPENDIX C**

### **MASS AND IMPACT CALCULATIONS**

# SECTION MODULUS FOR PLATFORM DUE TO IMPACT

C1



$C \equiv$  weight of cargo pod = 25,000 kg

$t \equiv$  weight of fuel tanks = 1,500 kg

$L \equiv$  force of legs

$f \equiv$  distance between the legs and the center of gravity of the tanks = 0.8 m

$l \equiv$  distance between legs = 6 m

$a \equiv$  acceleration = 10 lunar g's = 16.3 m/s<sup>2</sup>

FAS  $\equiv$  factor of safety = 5

$$\sum F = 0 \quad L = \frac{1}{2} (25,000 + 2(1,500)) a = 14,000 a \text{ N}$$

maximum moment at C,

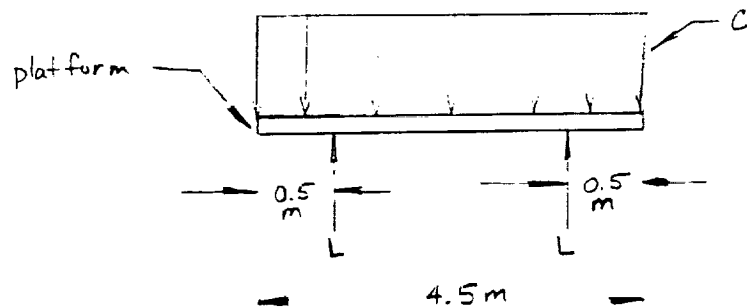
$$\sum M_c = 0 \quad M_{\max} = M_c = [14 \text{ kN} (3 \text{ m}) - 1.5 \text{ kN} (3.3 \text{ m})] a = 592.8 \text{ kN-m}$$

section modulus

$$Z = \frac{\text{FAS } M}{\sigma_y} = \frac{5 (592.8 \text{ kN-m})}{480,000 \frac{\text{N}}{\text{m}^2}} = 0.0062 \text{ m}^3 = 3.78 \times 10^2 \text{ in}^3$$

# SECTION MODULUS FOR PLATFORM DUE TO IMPACT

C2



$$C \equiv \text{distributed load of cargo pod} = \frac{25,000 \text{ kg} (16.3 \text{ m/s}^2)}{4.5 \text{ m}} = 90.55 \text{ kN/m}$$

$$\sum F = 0 \quad L = \frac{1}{2} (90.55 \frac{\text{kN}}{\text{m}}) (4.5 \text{ m}) = 203.75 \text{ kN}$$

$$\sum M = 0 \quad \text{maximum moment at center}$$

$$M_{\text{max}} = M_c = (-90.55 \frac{\text{kN}}{\text{m}}) (2.25 \text{ m}) (\frac{2.25 \text{ m}}{2}) + (203.75 \text{ kN}) (1.75 \text{ m}) = 127.34 \text{ kN m}$$

section modulus

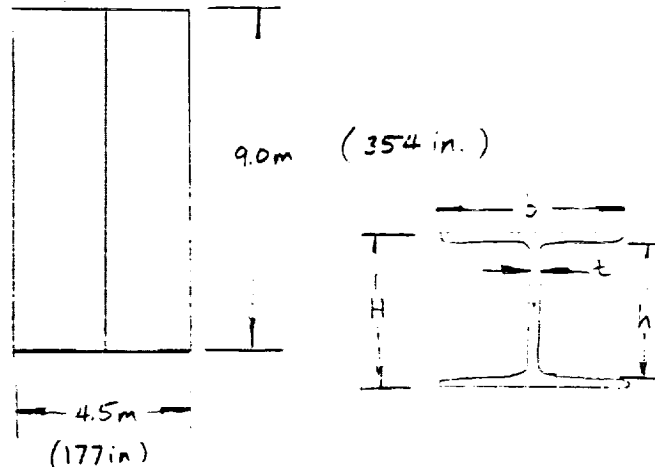
$$Z = \frac{5 M}{\sigma_y} = \frac{5 (127.34 \text{ kN m})}{480,000 \text{ kN/m}^2} = 0.00133 \text{ m}^3 = 80.38 \text{ in}^3$$

$\therefore$  Need more support along the 9.0 m direction. Simulate a platform with I-beams with appropriate Z's.

# PLATFORM MASS DETERMINATION

C3

From impact calculations need 3 beams in 9.0m direction  
and 2 beams in 4.5m direction.  
Simulate platform by 5 s-type I-beams, rigidly  
connected.



$$Z = \frac{I}{C} = 0.35 Ah \quad \text{for standard wide-flange beams}$$

$\swarrow$  web height  
 $\swarrow$  cross-sectional area

Given in Appendix C

3 beams:  $Z_{\text{tot}} = 0.00618 \text{ m}^3 = 3.768 \times 10^2 \text{ in}^3$  (needed)

$$Z_1 = 0.00206 \text{ m}^3 = 125.6 \text{ in}^3$$

select designation S20 x 75,  $Z = 128 \text{ in}^3$ ,  
area =  $22.0 \text{ in}^2$ , depth = 20.0 in, web thickness = 0.635 in  
flange: width = 6.385 in, average thickness = 0.795 in  
vol. =  $7788 \text{ in}^3$

$$\text{total volume} = 23364 \text{ in}^3 = 0.38317 \text{ m}^3$$

$$\text{mass} = \rho \text{ vol.} = (2800 \text{ kg/m}^3)(0.38317 \text{ m}^3) = 1072.9 \text{ kg}$$

$$\text{total folded mass} = 2145.8 \text{ kg}$$

2 beams:  $Z_{\text{tot}} = 0.00189 \text{ m}^3 = 1.55 \times 10^2 \text{ in}^3$  (needed)

$$Z_1 = 0.0009471 \text{ m}^3 = 57.75 \text{ in}^3$$

select designation S15 x 42.9,  $Z = 59.6 \text{ in}^3$ ,  
area =  $12.6 \text{ in}^2$ , depth = 15 in, web thickness = 0.411 in,  
flange: width = 5.501 in, average  $t = 0.622 \text{ in}$ ,  
volume =  $2.23 \times 10^3 \text{ in}^3$ , total vol. =  $4.46 \times 10^3 \text{ in}^3$

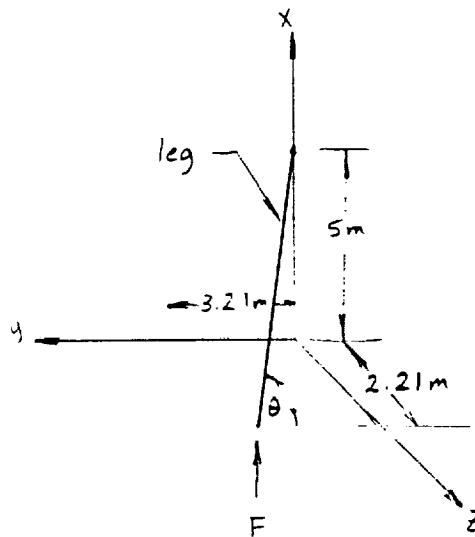
$$\text{mass} = 204.82 \text{ kg}$$

$$\text{TOTAL} = 2350.62 \text{ kg} = 5184 \text{ lb}$$



# LEGS NEEDED FOR IMPACT

C4



$$\text{Length of leg} = 6.34 \text{ m} (249.44 \text{ in})$$

$$\theta = \sin^{-1} \left( \frac{5}{6.34} \right) = 52^\circ$$

$$a \rightarrow (\text{factor of safety}) g_{\text{nom}} = 16.3 \text{ m/s}^2$$

$M \rightarrow$  Appendix E

$$F \equiv \text{impact force on one}$$

$$\text{leg} = \frac{1}{4} m a$$

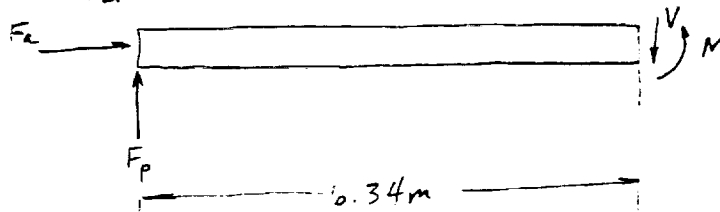
$$= \frac{1}{4} (34,351 \text{ kg}) (16.3 \text{ m/s}^2)$$

$$= 1.400 \times 10^2 \text{ kN}$$

Treat as a beam, neglect weight (due to the large impact force), cut at joint connecting to platform (that is where the greatest moment will be).

$$F_{\text{perpendicular}} = F \cos \theta = 1.4 \times 10^2 \text{ kN} (\cos 52^\circ) = 86.2 \text{ kN}$$

$$F_{\text{axial}} = F \sin \theta = 1.4 \times 10^2 \text{ kN} (\sin 52^\circ) = 110.3 \text{ kN}$$



$$\sum F = 0$$

$$F_p = V$$

$$\sum M = 0$$

$$F_p (6.34 \text{ m}) = M = 86.2 \text{ kN} (6.34 \text{ m}) = 546.5 \text{ kN}\cdot\text{m}$$

$$\sigma_x = \frac{M_y}{I}$$

$$\sigma = \frac{F_a}{A} \quad \text{compressive stress}$$

$$\sigma_{\text{allow}} = \frac{\sigma_y}{5} = \frac{480 \text{ MPa}}{5} = 96 \text{ MPa}$$

$$\text{need } S = \frac{M_{\text{max}}}{\sigma_{\text{allow}}} = \frac{546.5 \text{ kN}\cdot\text{m}}{96 \text{ MPa}} = 5.693 \times 10^{-3} \text{ m}^3 = 347.09 \text{ in}^3$$

(section modulus)

## LEGS NEEDED FOR IMPACT

C5

→ select W shape (wide-flange sections)

$S = 380 \text{ in}^3 = Z$  designated W 30 X 132, area =  $38.9 \text{ in}^2$ ,  
depth =  $30.31 \text{ in}$ , web  $t = 0.615 \text{ in}$ , flange width =  $10.545 \text{ in}$ ,  
thickness =  $1.00 \text{ in}$ .

Volume =  $A L$

$$= (38.9 \text{ in}^2) (249.44 \text{ in}) = 9.70 \times 10^3 \text{ in}^3 \\ = 0.159 \text{ m}^3$$

$$\text{mass} = \rho \text{ vol} = 2800 \frac{\text{kg}}{\text{m}^3} (0.159 \text{ m}^3)$$

$$\text{mass} = 446 \text{ kg} = 982.7 \text{ lb}$$

Now, for 4 legs total mass =  $1784 \text{ kg} = 3931 \text{ lb}$

Note: for comparison

$$\sigma_{\text{tensile}} = \frac{M}{Z} = \frac{546.5 \text{ kN} \cdot \text{m}}{6.265 \times 10^{-4} \text{ m}^3} = 8.723 \times 10^5 \text{ kPa}$$

$$\sigma_{\text{compressive}} = \frac{F_{\text{axial}}}{A} = \frac{110.3 \text{ kN}}{2.51 \times 10^{-2} \text{ m}^2} = 4.39 \times 10^6 \text{ Pa} \\ = 4.39 \times 10^3 \text{ kPa}$$

∴ can disregard  $\sigma_c$  in light of  $\sigma_t$ .

## **APPENDIX D**

### **DEFLECTION CALCULATIONS**

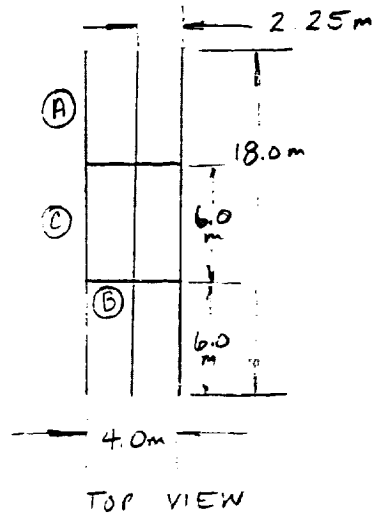
# PLATFORM DEFLECTION WHEN COVERED WITH REGOLITH

D1

Check deflections  
at (A) & (B).

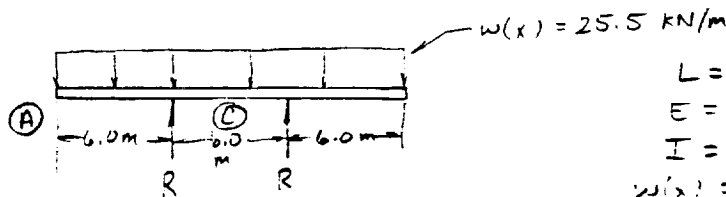
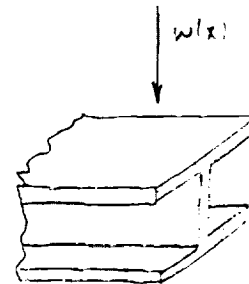
Regolith load  
=  $w(x)$   
(assumed uniformly  
distributed)

E & I values from  
reference.



Appendix B & D  
I-beams:

- 3 S20 x 75
- 2 S15 x 42.9



$$L = 6.0 \text{ m}$$

$$E = 72 \text{ GPa}$$

$$I = 1280 \text{ in}^4 = 5.33 \times 10^{-4} \text{ m}^4$$

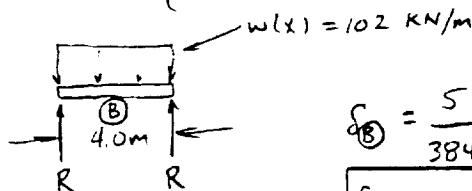
$$w(x) = 25.5 \text{ kN/m}$$

$$\delta_C = \frac{5 q L^4}{384 EI} = \frac{5 (25.5 \text{ kN/m}) (6 \text{ m})^4}{384 (72 \text{ GPa}) (5.33 \times 10^{-4} \text{ m}^4) (3)}$$

$$\delta_C = 0.004 \text{ m} = 0.15 \text{ in.} \quad (\text{simply-supported})$$

$$\delta_A = \frac{q L^4}{8 EI} = \frac{(25.5 \text{ kN/m}) (6 \text{ m})^4}{8 (72 \text{ GPa}) (5.33 \times 10^{-4} \text{ m}^4) (3)} = \boxed{0.036 \text{ m}} = \boxed{1.41 \text{ in.}}$$

(cantilever beam)



$$\delta_B = \frac{5 q L^4}{384 EI} = \frac{5 (102 \text{ kN/m}) (4 \text{ m})^4}{384 (72 \text{ GPa}) (1.86 \times 10^{-4} \text{ m}^4) (2)}$$

$$\delta_B = 0.013 \text{ m} = 0.5 \text{ in.} \quad (\text{simply supported})$$

## **APPENDIX E**

### **SUMMARY OF MASSES AND DEFLECTIONS**

## SUMMARY OF CALCULATIONS

E1

The platform is modeled by:

- 3 S20 x 75 I-beams, 18 m long, 358 kg each
- 2 S15 x 42.9 I-beams, 4.5 m long, 102.4 kg each

———— Appendix B

Each leg is modeled by:

- 1 S12 x 35 I-beam, 6.34 m long, 118 kg each

———— Appendix D

Weight : Inert Mass :	Platform	2351 kg
	legs	1784 kg
	tanks	3000 kg
	thermal protection system	2000 kg
	engines	1000 kg
	instruments	1000 kg
		<hr/>
		11,135 kg
		(24,558 lb)

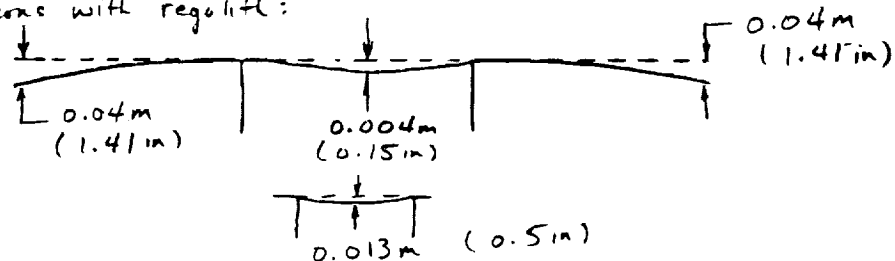
Propellant :	H <sub>2</sub>	4,000 kg
	O <sub>2</sub>	24,000 kg
		<hr/>
		28,000 kg (61,753 lb)

Payload : 25,000 kg

Total = 64,135 kg (141,448.4 lb)

All other values not in Appendix are from references.

Deflections with regolith:

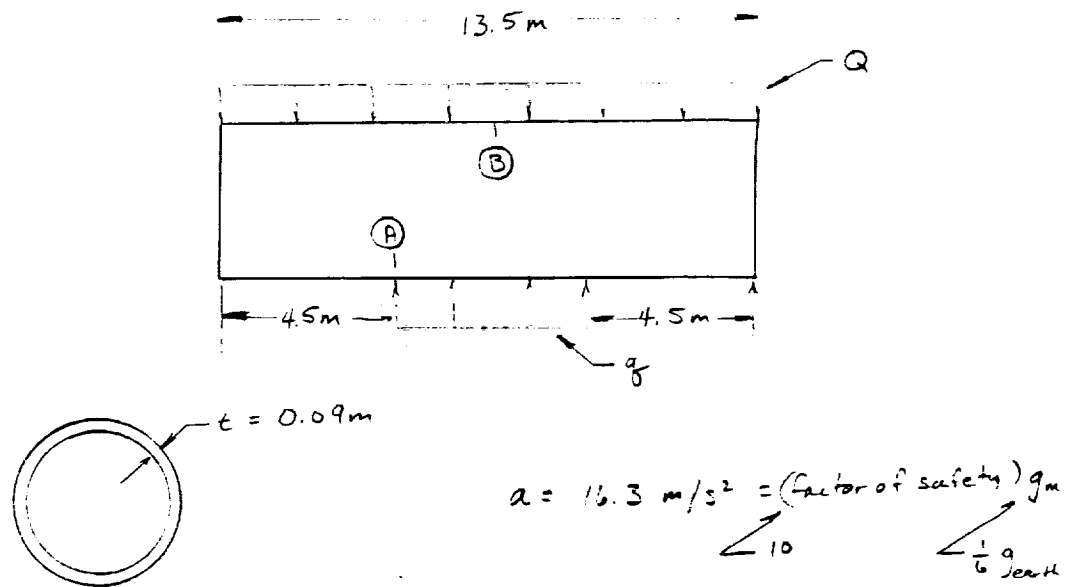


## **APPENDIX F**

### **IMPACT FORCES ON CARGO MODULE CALCULATIONS**

# IMPACT FORCES ON CARGO POD

F1



Assume: pod made of 7075 Al, uniform weight (Q), uniform support on platform (q).

$$Q = \frac{(25,000 \text{ kg})(16.3 \text{ m/s}^2)}{(13.5 \text{ m})} = 30.2 \text{ kN/m}$$

$$q = \frac{(25,000 \text{ kg})(16.3 \text{ m/s}^2)}{4.5 \text{ m}} = 90.7 \text{ kN/m}$$

$$M_A = (-30.2 \text{ kN/m})(4.5 \text{ m})(2.25 \text{ m}) = -30.58 \text{ kN}\cdot\text{m}$$

$$M_B = (-30.2 \text{ kN/m})(6.75 \text{ m})(3.375 \text{ m}) + (90.7 \text{ kN/m})(2.25 \text{ m})(1.125 \text{ m}) = -458.4 \text{ kN}\cdot\text{m}$$

$$\text{total } \sigma = \frac{M c}{I} = \frac{(4)(458.4 \text{ kN}\cdot\text{m})(2.2 \text{ m})}{\pi ((2.2)^4 - (2.11)^4)} = 356.24 \text{ kPa}$$

$$\sigma < \sigma_y = 480 \text{ MPa} \quad \therefore \text{Will never break.}$$



## **APPENDIX G**

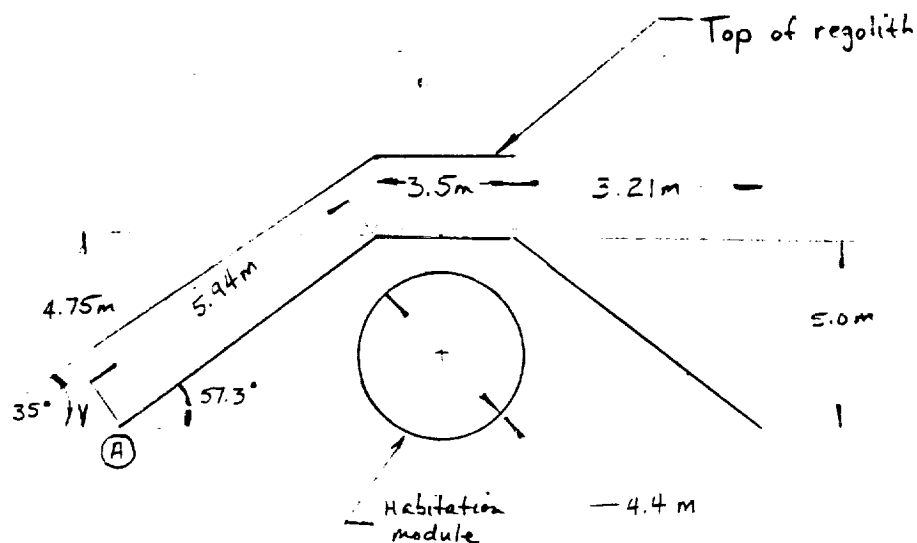
### **MAXIMUM REGOLITH PRESSURE CALCULATIONS**

## MAXIMUM REGOLITH PRESSURE

G1

scale:  $\text{---} 1\text{m}$

The allowable angle that regolith can be piled is  $35^\circ$ .  
Regolith density from reference.



The maximum pressure will be at (A).

$$P_{\max} = \rho g h = (1740 \text{ kg/m}^3) \frac{1}{6} (9.8 \text{ m/s}^2) (4.75 \text{ m})$$

$$P_{\max} = 13.5 \text{ kPa}$$

The pressure on top is:

$$P_{\text{top}} = \rho g h = (1740 \text{ kg/m}^3) \frac{1}{6} (9.8 \text{ m/s}^2) (2.0 \text{ m})$$

$$P_{\text{top}} = 5.7 \text{ kPa}$$